TEC REPORT NO. R-2004-289
MIKRONITE TECHNOLOGIES
RESIDUAL STRESS SUMMARY
TEC WON NO. 50816

Submitted to:

Mikronite Technologies
511 Washington Ave.
Carlstadt, NJ 07072

Submitted by:

TEC
10737 Lexington Dr.
Knoxville, TN 37932-3294
865-966-5856
Fax: 865-675-1241

Prepared by: Beth Matlock 8-19-04
Senior Materials Engineer

Reviewed by: Beth Matlock 8-19-04
Senior Materials Engineer

August 19, 2004

This Laboratory is accredited by the American Association for Laboratory Accreditation (A2LA) and the results shown in this test report have been determined in accordance with the Laboratory's terms of accreditation unless stated otherwise in the report.

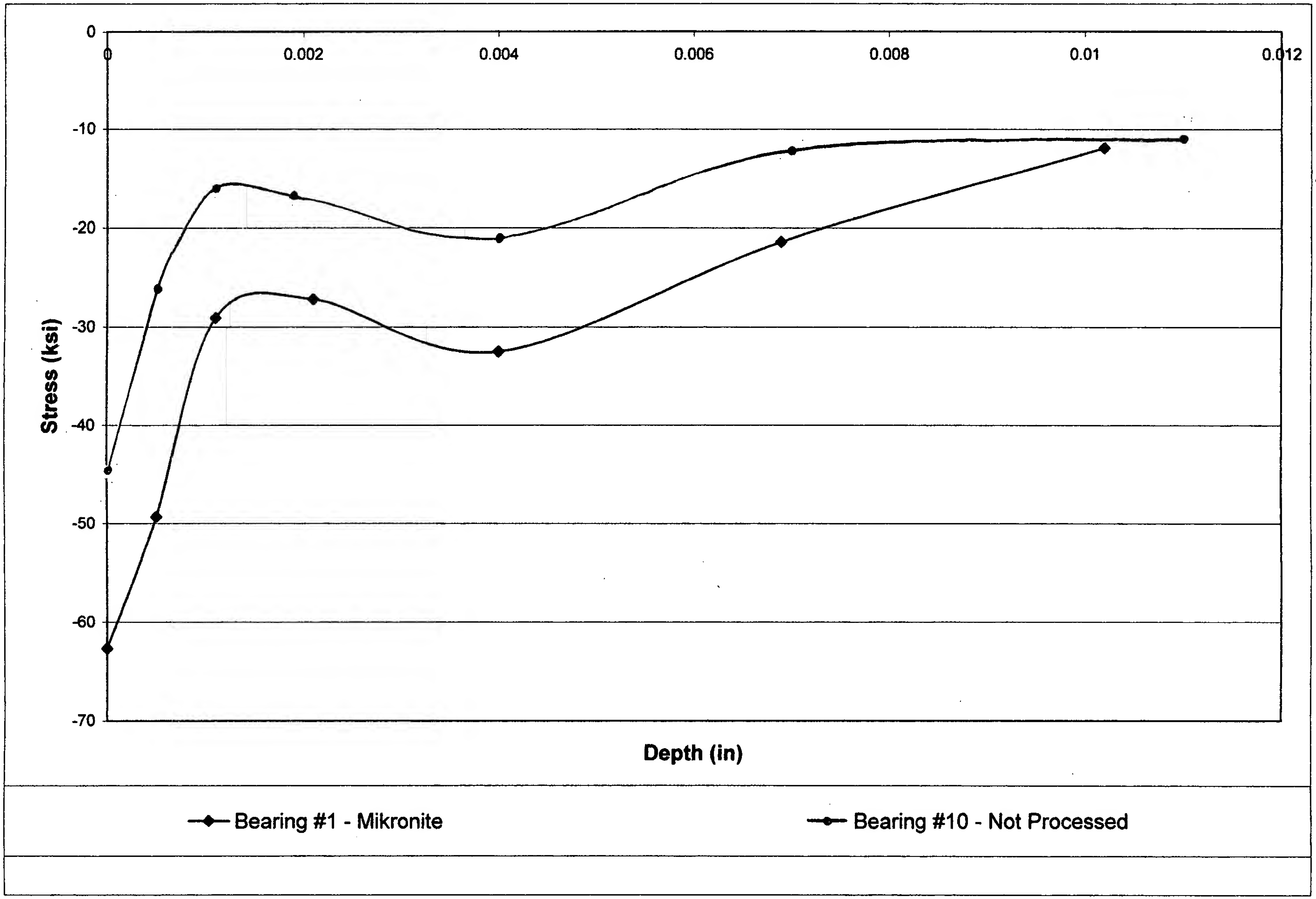
SUMMARY REPORT
MIKRONITE TECHNOLOGIES
RESIDUAL STRESS SUMMARY
Outer Bearing Raceways

Depth, in	Circumferential Residual Stress, ksi			Error, ksi
	As Measured	Corrected for Stress Gradient	Corrected for Layer Removal	
		1. Bearing #1, OD		
0.0000	–56.0	–62.7	–62.7	±2.8
0.0005	–43.7	–49.3	–49.3	±3.1
0.0011	–26.9	–29.2	–29.1	±3.5
0.0021	–27.7	–27.5	–27.2	±2.4
0.0040	–32.7	–32.9	–32.5	±2.3
0.0069	–21.4	–22.1	–21.4	±3.9
0.0102	–12.0	–12.7	–11.9	±1.6
		2. Bearing #5, OD		
0.0000	–67.4	–84.1	–84.1	±3.7
0.0005	–26.1	–36.3	–36.2	±3.3
0.0011	–13.8	–15.4	–15.2	±2.2
0.0019	–20.2	–19.5	–19.3	±1.5
0.0039	–22.1	–22.1	–21.7	±2.9
0.0072	–14.0	–14.7	–14.2	±3.1
0.0105	–0.2	–1.1	–0.5	±2.0
		3. Bearing #7, OD		
0.0000	–59.2	–66.4	–66.4	±2.6
0.0005	–40.9	–46.6	–46.5	±3.5
0.0012	–26.8	–27.7	–27.5	±2.7
0.0020	–36.0	–34.3	–34.1	±2.0
0.0039	–46.5	–46.1	–45.6	±3.4
0.0072	–39.8	–39.7	–38.7	±3.6
0.0099	–48.2	–47.6	–46.3	±3.6

SUMMARY REPORT
MIKRONITE TECHNOLOGIES
RESIDUAL STRESS SUMMARY
Outer Bearing Raceways

Depth, in	Circumferential Residual Stress, ksi			Error, ksi
	As Measured	Corrected for Stress Gradient	Corrected for Layer Removal	
		4. Bearing #8, OD		
0.0000	–83.1	–94.4	–94.4	±2.9
0.0006	–48.8	–53.9	–53.7	±4.3
0.0012	–53.3	–52.9	–52.7	±3.0
0.0019	–51.6	–51.7	–51.3	±2.8
0.0041	–51.8	–51.6	–50.9	±3.9
0.0072	–55.0	–54.6	–53.4	±3.2
0.0100	–64.3	–63.9	–62.1	±2.7
		5. Bearing #9, OD		
0.0000	–14.7	-	-	±3.0
		6. Bearing #10, OD		
0.0000	–37.0	-	-	±2.7

Contents: Summary Report: 4 pages
Appendix: Detailed Explanation of Residual Stress Analysis Data Sheet: 6 pages; Computer-Generated Data Sheets: 68 pages



0
-10
-20
-30
-40
-50
-60
-70
Stress (ksi)
0
0.002
0.004
0.006
0.008
0.01
0.012
Depth (in)
Bearing #1 - Mikronite
Bearing #10 - Not Processed

American Association for Laboratory Accreditation

SCOPE OF ACCREDITATION TO ISO/IEC 17025-1999

TEC MATERIALS TESTING LABORATORY
10737 Lexington Drive
Knoxville, TN 37932-3294
Carol Bailey Phone: 865 966 5856

MECHANICAL

Valid To: February 28, 2006 Certificate Number: 1033-01

In recognition of the successful completion of the A2LA evaluation process, accreditation is granted to this laboratory to perform the following tests on crystalline metals, polymers and ceramics:

Test Technology	Test Methods
Electropolishing for Subsurface Analysis of Residual Stress and Retained Austenite	LP 321
X-ray Diffraction (XRD)	
Residual Stress Measurement and Analysis	ASTM E915, SAE J784a
Retained Austenite Measurement and Analysis	ASTM E975, SAE SP-453

This laboratory offers field-testing. All of the above testing is performed in the field, as well as in the laboratory, both of which are covered by A2LA accreditation.

Peter Abn

5301 Buckeystown Pike, Suite 350 • Frederick, MD 21704-8373 • Phone: 301-644 3248 • Fax: 301-662 2974

TEC REPORT NO. R-2004-304
MIKRONITE TECHNOLOGIES
RESIDUAL STRESS SUMMARY
TEC WON NO. 50908

Submitted to:

Mikronite Technologies
511 Washington Ave.
Carlstadt, NJ 07072

Submitted by:

TEC
10737 Lexington Dr.
Knoxville, TN 37932-3294
865-966-5856
Fax: 865-675-1241

Prepared by: Beth Matlock 8-31-04
Senior Materials Engineer

Reviewed by: Beth Matlock 8-31-04
Senior Materials Engineer

August 31, 2004

This Laboratory is accredited by the American Association for Laboratory Accreditation (A2LA) and the results shown in this test report have been determined in accordance with the Laboratory's terms of accreditation unless stated otherwise in the report.

SUMMARY REPORT
MIKRONITE TECHNOLOGIES
RESIDUAL STRESS SUMMARY
Outer Bearing Raceways

Depth, in	Circumferential Residual Stress, ksi As Measured	Corrected for Stress Gradient	Corrected for Layer Removal	Error, ksi
1. Raceway #9				
0.0000	−15.0	−9.0	−9.0	±2.7
0.0006	−32.7	−28.0	−28.0	±1.8
0.0011	−40.8	−39.8	−39.7	±3.3
0.0020	−34.8	−35.4	−35.2	±2.3
0.0039	−29.9	−29.6	−29.2	±2.9
0.0073	−40.3	−40.3	−39.5	±3.3
0.0099	−34.9	−35.5	−34.4	±2.4
2. Raceway #10				
0.0000	−37.3	−44.7	−44.7	±2.5
0.0005	−21.7	−26.3	−26.2	±1.3
0.0011	−15.6	−16.1	−16.0	±2.3
0.0019	−17.4	−16.8	−16.7	±3.5
0.0040	−21.1	−21.2	−21.0	±2.9
0.0070	−12.2	−12.6	−12.1	±2.1
0.0110	−11.3	−11.4	−10.8	±1.6

Contents: Summary Report: 3 pages
Appendix: Detailed Explanation of Residual Stress Analysis Data Sheet: 6 pages; Computer-Generated Data Sheets: 32 pages

TEC REPORT NO. R-2004-286
MIKRONITE TECHNOLOGIES
RESIDUAL STRESS SUMMARY
TEC WON NO. 50797

Submitted to:

Mikronite Technologies
511 Washington Ave.
Carlstadt, NJ 07072

Submitted by:

TEC
10737 Lexington Dr.
Knoxville, TN 37932-3294
865-966-5856
Fax: 865-675-1241

Prepared by: Beth Matlock 8-13-04
Senior Materials Engineer

Reviewed by: Beth Matlock 8-13-04
Senior Materials Engineer

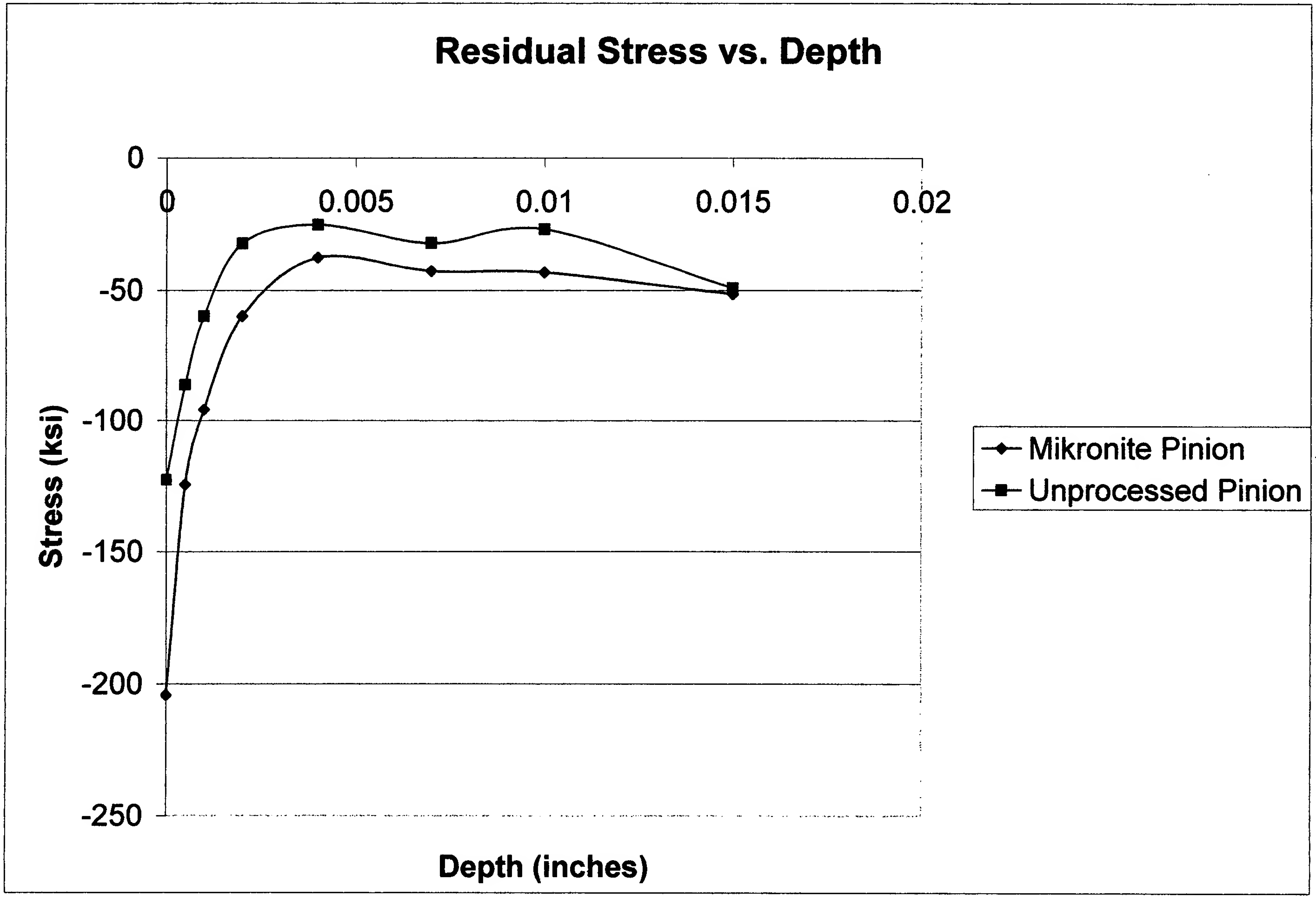
August 13, 2004

This Laboratory is accredited by the American Association for Laboratory Accreditation (A2LA) and the results shown in this test report have been determined in accordance with the Laboratory's terms of accreditation unless stated otherwise in the report.

SUMMARY REPORT
MIKRONITE TECHNOLOGIES
RESIDUAL STRESS SUMMARY
Pinion Gears

Depth, in	Residual Stress, Root to Tip Direction, ksi			Error, ksi
	As Measured	Corrected for Stress Gradient	Corrected for Layer Removal	
	1. Gear RM, Mid-Tooth			
0.0000	−142.3	-	-	±5.8
	2. Gear R, Mid-Tooth			
0.0000	−158.0	-	-	±7.4
	3. Gear M, Mid-Tooth			
0.0000	−176.9	−204.3	−204.3	±4.6
0.0005	−107.8	−125.3	−124.6	±2.0
0.0010	−89.2	−96.8	−95.7	±4.2
0.0020	−57.1	−61.5	−59.8	±3.7
0.0040	−39.6	−40.1	−37.6	±3.0
0.0070	−46.7	−46.3	−42.7	±4.0
0.0100	−48.3	−48.0	−43.3	±3.9
0.0150	−58.5	−58.2	−51.4	±2.9
	4. Gear U, Mid-Tooth			
0.0000	−111.6	−122.7	−122.7	±4.6
0.0005	−75.3	−86.6	−86.2	±3.5
0.0010	−52.4	−60.5	−59.8	±3.2
0.0020	−30.8	−33.4	−32.3	±2.6
0.0040	−27.0	−26.9	−25.3	±2.8
0.0070	−34.6	−34.4	−32.1	±3.7
0.0100	−30.4	−30.0	−27.0	±3.3
0.0150	−54.7	−53.8	−49.1	±2.7

Contents: Summary Report: 3 pages
Appendix: Detailed Explanation of Residual Stress Analysis Data Sheet: 6 pages; Computer-Generated Data Sheets: 40 pages



Residual Stress vs. Depth
0
-50
-100
-150
-200
-250
0
0.005
0.01
0.015
0.02
Stress (ksi)
Depth (inches)
Mikronite Pinion
Unprocessed Pinion

TEC MATERIALS TESTING LABORATORY
CERTIFICATIONS AND CLARIFYING STATEMENTS

Quality System Registration: Certificate Number 03-R0442

This quality system meets the requirements of the ISO 9001:2000 standard for x-ray diffraction testing on materials relating to the automotive, aerospace/aviation, ceramic, and other general manufacturing industries, especially as they relate to process control and quality control; and Government, academic, and commercial research and development laboratories; and related services including electropolishing.

Laboratory Accreditation: Certificate Number 1033.01

The American Association for Laboratory Accreditation (A2LA) has accredited this laboratory for technical competence in the **field of Mechanical Testing**. The Lab's accreditation covers the specific tests and test methods, specifically the ASTM standards, SAE guidelines, and references that are listed on the agreed Scope of Accreditation (**see attached**). This laboratory meets the requirements of ISO/IEC 17025:1999 "General Requirements for the Competence of Testing and Calibration Laboratories" and any additional program requirements in the identified fields of testing.

Clarifying Statements

The following clarifying statements apply to test results reported herein:

1. These X-ray data are representative of measurements taken of the top few atomic layers at a specific location in a specific direction. Measurement assumptions and metallurgical conditions affect the precision and validity of the data.

2. These test results relate only to the parts tested.

3. This test report and test data shall not be reproduced except in full without the written approval of the Laboratory.

4. The scope of the laboratory's A2LA endorsement is shown above.

5. Products, materials, or other items are in no way approved or endorsed by A2LA without A2LA's explicit approval.

6. Absent a pre-approved sampling procedure, these results do not extend to a sample or samples of a lot or batch from which the sample was drawn.

7. This report does not include or imply an expert opinion as to the serviceability of the sample or batch, or its suitability for a specific purpose.

8. Material removal by electropolishing is accomplished by estimating the time required to remove a certain amount of material. Since electropolishing rates may vary, even through the same sample, targeted depths may inadvertently be exceeded.

February 23, 2004

General Electric Series

WRITTEN FOR THE ADVANCEMENT OF ENGINEERING PRACTICE

AN INTRODUCTION TO POWER SYSTEM ANALYSIS
by Frederick S. Rothe

D-C POWER SYSTEMS FOR AIRCRAFT
by R. H. Kaufmann and H. J. Finison

TRANSIENTS IN POWER SYSTEMS
by Harold A. Peterson

SERVOMECHANISMS AND REGULATING SYSTEM DESIGN, VOLUME I
by Harold Chestnut and Robert W. Mayer

TRANSFORMER ENGINEERING
by the late L. F. Blume, A. Boyajian, G. Camilli, T. C. Lennox, S. Minneci, and V. M. Montsinger, *Second Edition*

CIRCUIT ANALYSIS OF A-C POWER SYSTEMS, TWO VOLUMES
by Edith Clarke

CAPACITORS FOR INDUSTRY
by W. C. Bloomquist, C. R. Craig, R. M. Partington, and R. C. Wilson

PROTECTION OF TRANSMISSION SYSTEMS AGAINST LIGHTNING
by W. W. Lewis

MAGNETIC CONTROL OF INDUSTRIAL MOTORS
by Gerhart W. Heumann

POWER SYSTEM STABILITY
Volume I—Steady State Stability; Volume II—Transient Stability;
by Selden B. Crary

MATERIALS AND PROCESSES
by J. F. Young, *Second Edition*

MODERN TURBINES
by L. E. Newman, A. Keller, J. M. Lyons, and L. B. Wales;
edited by L. E. Newman

ELECTRIC MOTORS IN INDUSTRY
by D. R. Shoults and C. J. Rife; edited by T. C. Johnson

MATERIALS and PROCESSES

JAMES F. YOUNG
Major Appliance Division
General Electric Company
Erie, Pennsylvania

SECOND EDITION

One of a series written in the interest of the General Electric Engineering Educational Programs

JOHN WILEY & SONS, INC., NEW YORK
CHAPMAN & HALL, LTD., LONDON · 1954

Library of Congress Catalog Card Number: 53–12224

Printed in the United States of America

In memory of

Dr. A. R. STEVENSON, Jr.

4.33 THEORIES OF STRENGTH FAILURE

Considerable study has been given to the correlation of elastic theory with failure of materials. Particular interest has been placed on correlating strength failure under combined stress with simple tension tests. Five of the theories advanced are:

(*a*) Maximum normal (tensile) stress at any point under combined stress equal to the tensile stress at failure in simple tension constitutes failure (Rankin's theory).

(*b*) Maximum strain at any point under combined stress equal to the strain at failure in simple tension constitutes failure (St. Venant's theory).

(*c*) Maximum shearing stress at any point under combined stress equal to shearing stress at failure in simple tension constitutes failure (Guest's theory).

(*d*) Maximum strain energy at any point under combined stress equal to this energy at failure in simple tension test constitutes failure (Beltrami and Haigh).

(*e*) Maximum distortion energy at any point under combined stress equal to this energy at failure in simple tension test constitutes failure (Hencky, Von Mises, and others).

The maximum-stress theory (Rankin) appears to have close agreement with experiment for brittle materials. For both brittle and ductile materials, the maximum-shearing-stress theory appears somewhat conservative but is often used because of its simplicity over strain-energy and distortion-energy theories. The latter is probably in closest agreement with available data for ductile materials. Use of the maximum-shearing-stress theory is aided by determining the maximum shear stress on oblique planes by use of Mohr's circle or similar analysis.

Some work has been done to apply these and other theories to plastic flow and fatigue. For discussion of these topics see the works of Nádai and Marin listed at the end of the chapter.

4.34 STRESS DETERMINATIONS

The stresses present in a part can be calculated mathematically, using elastic theory when the shapes are not complicated and when the magnitudes of the applied loads are known. Often, however, the part shape is complicated and does not lend itself to accurate analysis. For such parts the stresses may be determined by one of several experimental methods. Sometimes photoelastic testing may be employed by studying a suitable transparent plastic model under polarized light. This method is particularly helpful for parts containing stress raisers, although in ductile materials some yielding may take place to reduce the stress concentration, thus permitting a larger load to be supported. Dynamic loads and the maximum stresses they produce may be measured in simulated tests on models or in actual service tests on parts through use of stress coatings (brittle lacquers) or strain gages. The stress-coat method involves coating the part prior to loading. The lacquer obtains a controlled brittleness in curing. Under test it will crack when local tensile yielding reaches a limiting value, thus indicating regions of high stress and strain. Relaxation methods can be used for detecting high compressive stress. In either application, careful control of the lacquers is essential to good results. The strain-gage method, using either carbon gages or nichrome wire gages whose resistance changes with local strain (inductive and capacitance gages are also available), provides a more accurate measure of strain. But the points of highest stress must be anticipated, since equipment and space limits the number of gages that can be applied.

Residual Stresses. Analysis of residual stresses in fabricated parts is often important, since such stresses may be additive with applied load stresses and may decrease the strength of the part. Four general methods have been used for this purpose.

The most widely used method is based on the elastic strain that will result upon release of the "locked-up" load by removal of some of the material. One procedure, proposed by G. Sachs, involves drilling out cylinders or tubes in several steps and measuring diameters and lengths. Original residual stresses are then calculated from the relaxations. Strain gages or other accurate strain-measuring equipment is required. Residual stresses in tubes may also be determined by change in curvature resulting from parting with acid or an abrasive wheel. The stresses in plates may be determined by curvature change upon machining from the surface.

A second method involves use of brittle lacquers which are coated and cured on the surface. A hole is then drilled through the lacquer. Star-shaped relaxation patterns indicate residual tension at the point drilled; concentric circles indicate compression. Magnitude of the stress is determined through repeated trials with calibrated coatings.

A third method is to detect by X-ray diffraction the difference in atom spacing in the material as a result of stress. This method is

ASM

METALS Reference Book

Third Edition

Editor
Michael Bauccio

Acquisitions/Editorial
Veronica Flint

Technical Editor
Sunniva Collins

Production Project Manager
Suzanne Hampson

Production Project Specialist
Dawn Levicki

ASM International
The Materials Information Society

First printing, December 1993
Second printing, September 1994

This book is a collective effort involving hundreds of technical specialists. It brings together a wealth of information from worldwide sources to help scientists, engineers, and technicians solve current and long-range problems.

Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

Library of Congress Cataloging in Publication Data

ASM International®
Materials Park, OH 44073-0002

ASM metals reference book/editor, Michael Bauccio.—3rd ed. p. cm.
ISBN: 0-87170-478-1
1. Metals—Handbooks, manuals, etc. 2. Metal-work—Handbooks, manuals, etc.
I. Bauccio, Michael. II. American Society for Metals.
III. Title: A.S.M. metals reference book.
IV. Title: Metals reference book. TA459.A78 1993
620.1'6—dc20
93-28716 CIP

Printed in the United States of America

be reducing to one oxide but not to another oxide.

reducing flame. (1) A gas flame produced with excess fuel in the inner flame. (2) A gas flame resulting from combustion of a mixture containing too much fuel or too little air.

reduction. (1) In cupping and deep drawing, a measure of the percentage decrease from blank diameter to cup diameter, or of diameter reduction in redrawing. (2) In forging, rolling and drawing, either the ratio of the original to final cross-sectional area or the percentage decrease in cross-sectional area. (3) A reaction in which there is a decrease in valence resulting from a gain in electrons. Contrast with *oxidation*.

reduction cell. A pot or tank in which either a water solution of a salt or a fused salt is reduced electrolytically to form free metals or other substances.

reduction in area (RA). The difference between the original cross-sectional area of a tensile specimen and the smallest area at or after fracture as specified for the material undergoing testing. Also known as reduction of area.

reel. (1) A spool or hub for coiling or feeding wire or strip. (2) To straighten and planish a round bar by passing it between contoured rolls.

reel breaks. Transverse breaks or ridges on successive inner laps of a coil that results from crimping of the lead end of the coil into a gripping segmented mandrel. Also called reel kinks.

reference electrodes. A nonpolarizable *electrode* with a known and highly reproducible *potential* used for potentiometric and voltammetric analyses. See also *calomel electrode*.

reference material. In materials characterization, a material of definite composition that closely resembles in chemical and physical nature the material with which an analyst expects to deal; used for calibration or standardization. See also *standard reference material*.

refining. The branch of *process metallurgy* dealing with the purification of crude or impure metals. Compare with *extractive metallurgy*.

reflowing. Melting of an electrodeposit followed by solidification. The surface has the appearance and physical characteristics of a hot dipped surface (especially tin or tin alloy plates). Also called flow brightening.

refractory. (1) A material (usually an inorganic, nonmetallic, ceramic material) of very high melting point with properties that make it suitable for such uses as furnace linings and kiln construction. (2) The quality of resisting heat.

refractory alloy. (1) A heat-resistant alloy. (2) An alloy having an extremely high melting point. See also *refractory metal*. (3) An alloy difficult to work at elevated temperatures.

refractory metal. A metal having an extremely high melting point and low vapor pressure; for example, niobium (columbium), tantalum, molybdenum, tungsten, and rhenium.

regenerator. Same as *recuperator* except that the gaseous products or combustion heat brick checkerwork in a chamber connected to the exhaust side of the furnace while the incoming air and fuel are being heated by the brick checkerwork in a second chamber, connected to the entrance side. At intervals, the gas flow is reversed so that incoming air and fuel contact hot checkerwork while that in the second chamber is being reheated by exhaust gases.

regulator. A device for controlling the delivery of welding or cutting gas at some substantially constant pressure.

reliability. A quantitative measure of the ability of a product or service to fulfill its intended function for a specified period of time.

relief. The result of the removal of tool material behind or adjacent to the cutting edge to provide clearance and prevent rubbing (heel drag). See also *relief angle*.

relief angle. The angle formed between a relieved surface and a given plane tangent to a cutting edge or to a point on a cutting edge. Also known as clearance angle. See also the figure accompanying *single-point tool*.

relieving. Buffing or other abrasive treatment of the high points of an embossed metal surface to produce highlights that contrast with the finish in the recesses.

remanence. The magnetic induction remaining in a magnetic circuit after removal of the applied magnetizing force. Sometimes called remanent induction.

repressing. The application of pressure to a previously pressed and sintered powder metallurgy compact, usually for the purpose of improving some physical or mechanical property or for dimensional accuracy.

residual elements. Small quantities of elements unintentionally present in an alloy.

residual stress. (1) The stress existing in a body at rest, in equilibrium, at uniform temperature, and not subjected to external forces. Often caused by the forming or thermal processing curing process. (2) An internal stress not depending on external forces resulting from such factors as cold working, phase changes, or temperature gradients. (3) Stress present in a body that is free of external forces or thermal gradients. (4) Stress remaining in a structure or member as a result of thermal or mechanical treatment or both. Stress arises in fusion welding primarily because the weld metal contracts on cooling from the solidus to room temperature.

resilience. (1) The amount of energy per unit volume released on unloading. (2) The capacity of a material, by virtue of high yield strength and low elastic modulus, to exhibit considerable elastic recovery on release of load.

resinoid wheel. A grinding wheel bonded with a synthetic resin.

resist. (1) Coating material used to mask or protect selected areas of a substrate from the action of an etchant, solder, or plating. (2) A material applied to prevent flow of brazing filler metal into unwanted areas.

resistance brazing. A resistance joining process in which the workpieces are heated locally and filler metal that is preplaced between the workpieces is melted by the heat obtained from resistance to the flow of electric current through the electrodes and the work. In the usual application of resistance brazing, the heating current is passed through the joint itself.

resistance seam welding. A resistance welding process which produces coalescence at the faying surfaces by the heat obtained from resistance to electric current through workpieces that are held together under pressure by electrode wheels. The resulting weld is a series of overlapping resistance spot welds made progressively along a joint by rotating the electrodes.

resistance soldering. Soldering in which the joint is heated by electrical resistance. Filler metal is either face fed into the joint or preplaced in the joint.

resistance spot welding. A process in which faying surfaces are joined in one or more spots by the heat generated by resistance to the flow of electric current through workpieces that are held together under force by electrodes. The contacting surfaces in the region of current concentration are heated by a short-time pulse of low-voltage, high-amperage current to form a fused nugget of weld metal. When the flow of current ceases, the electrode force is maintained while the weld metal rapidly cools and solidifies. The electrodes are retracted after each weld, which usually is completed in a fraction of a second.

INTRODUCTION

As we know, all manufacturing processes introduce residual stress into mechanical parts, which influences its fatigue behaviour and breaking strength and even its corrosion resistance. Few metalworking methods exist which do not produce new stresses. The role of residual stress is therefore very important when designing mechanical parts. Over the last few years, an increasing number of studies have been carried out to understand the effects of residual stress on mechanical performance. This article attempts to present a global approach to including residual stress in expected fatigue life calculations, and the possibility of introducing it into mechanical engineering design offices. We will first present the definitions and origins of residual stress according to production methods. We will then show the beneficial and harmful effects of residual stress on the resistance of structures or industrial components depending on whether they are tensile or compressive. The methods used to include residual stress in calculation of the fatigue life will also be analysed. We will lastly show the problems involved in correctly adapting these modelling techniques for use in design offices and the industrial consequences of taking residual stress into account on quality assurance control procedures.

DEFINITION OF RESIDUAL STRESS

Residual stress is usually defined as the stress which remains in mechanical parts which are not subjected to any outside stresses. Residual stress exists in practically all rigid parts, whether metallic or not (wood, polymer, glass, ceramic, etc). It is the result of the metallurgical and mechanical history of each point in the part and the part as a whole during its manufacture. It exists at different levels, generally divided into three, depending on the scale on which the stress is observed [1]:

- 3rd level stress, on the crystal scale. At this level, the outside limit of the notion of stress is reached. It corresponds to the actions created by all the different types of crystalline defects: vacancies, interstitial compounds, substitute atoms, dislocations, stacking defects, twin crystals and grain joints.

- 2nd level stress, due to the heterogeneity and anisotropy of each crystal or grain in a polycrystalline material. In the presence of mechanical stress (uniform traction of a smooth test specimen, for example), certain grains oriented in the right direction will reach the yield point before others, which results in heterogeneous behaviour when the load is eliminated. The resilience will therefore develop differently or more or less freely according to the grains, thus producing non-nil stresses (2nd level residual stress). However, the average of these stresses, that is, the general resultant along the traction axis, will be nil at the end of the test (1st level residual stress). This type of stress can be measured by X-ray diffraction.

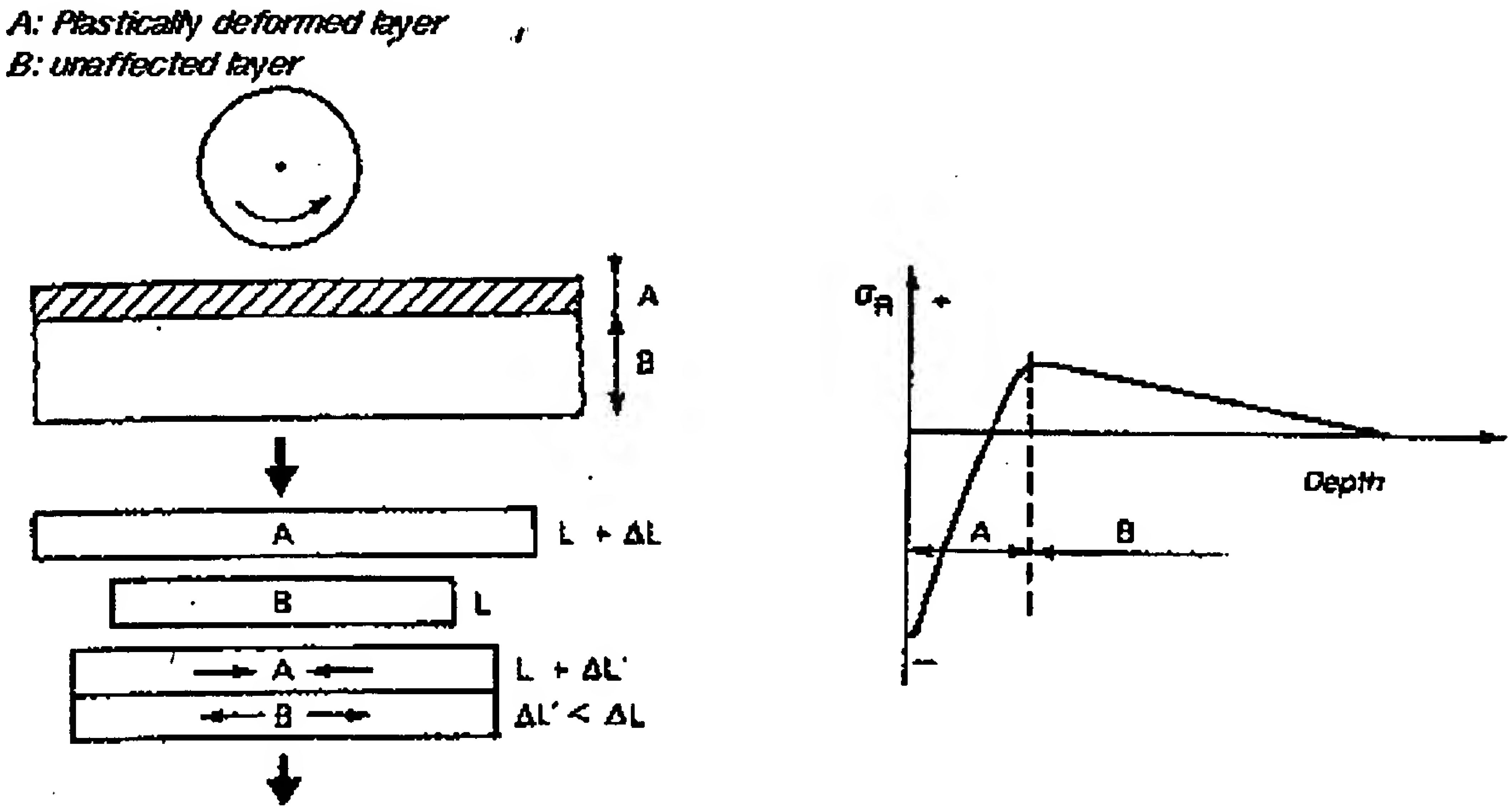
- 1st level or macroscopic residual stress, affecting a large number of grains or the whole of the mechanical part. It can be measured using gauges, for example, which detect the deformation produced, or X-rays.

These three types of residual stress occur one after the other. It is first level or macroscopic residual stress which is of interest to mechanical engineers and design offices. However, 2nd level residual stress is also very important, since it is an indicator of strain-hardening and damage to the material [2].

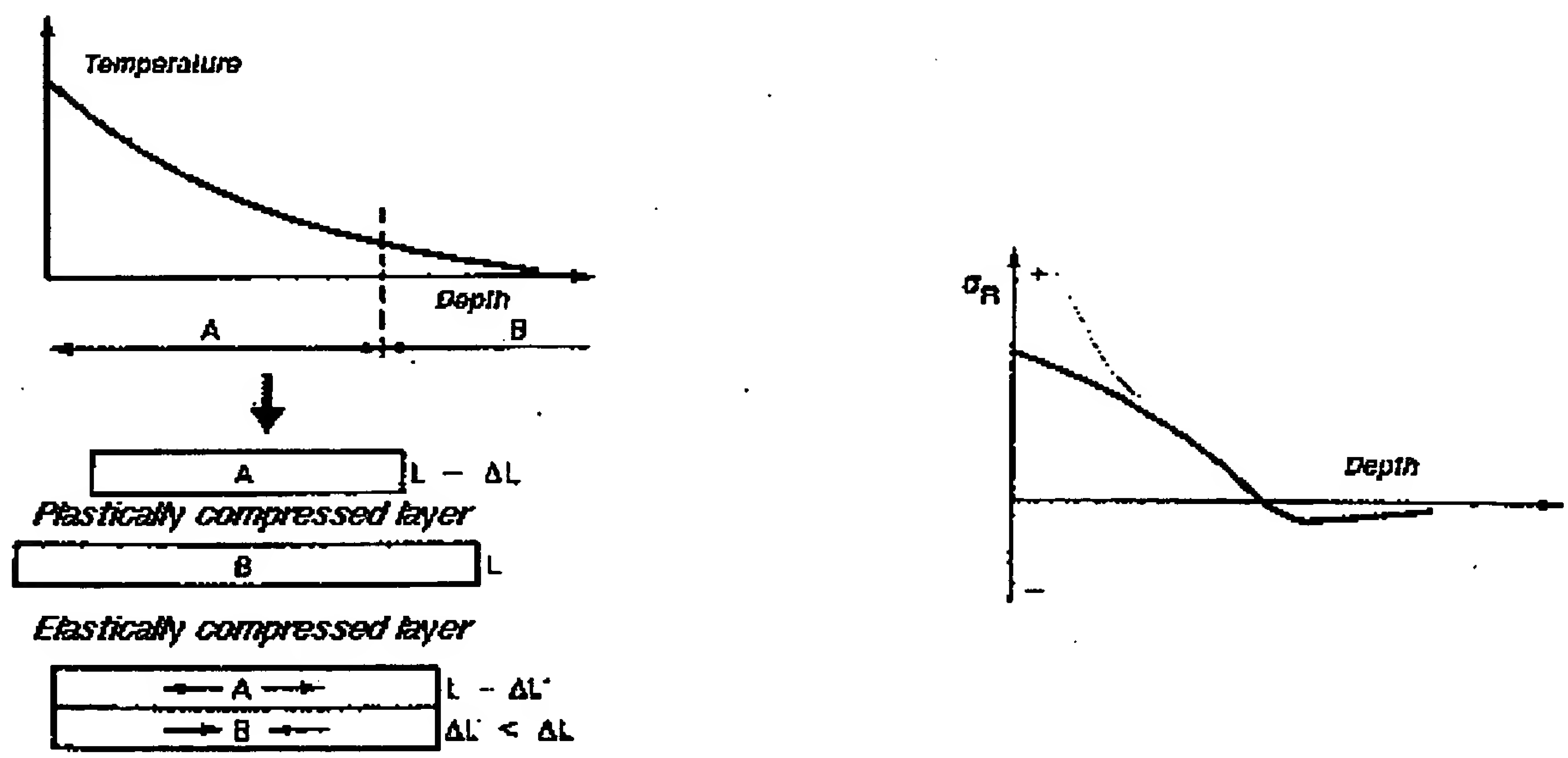
ORIGIN OF RESIDUAL STRESS

The origin of residual stress is wide and varied. It can be divided into three categories – mechanical, thermal and metallurgical (Figure 1). These different factors often combine to produce residual stress. For example, in the case of grinding, stress is produced by all three processes. Figures 2a-2c indicate the mechanisms which create residual stress in this particular case and shows the complexity of the origin of residual stress.

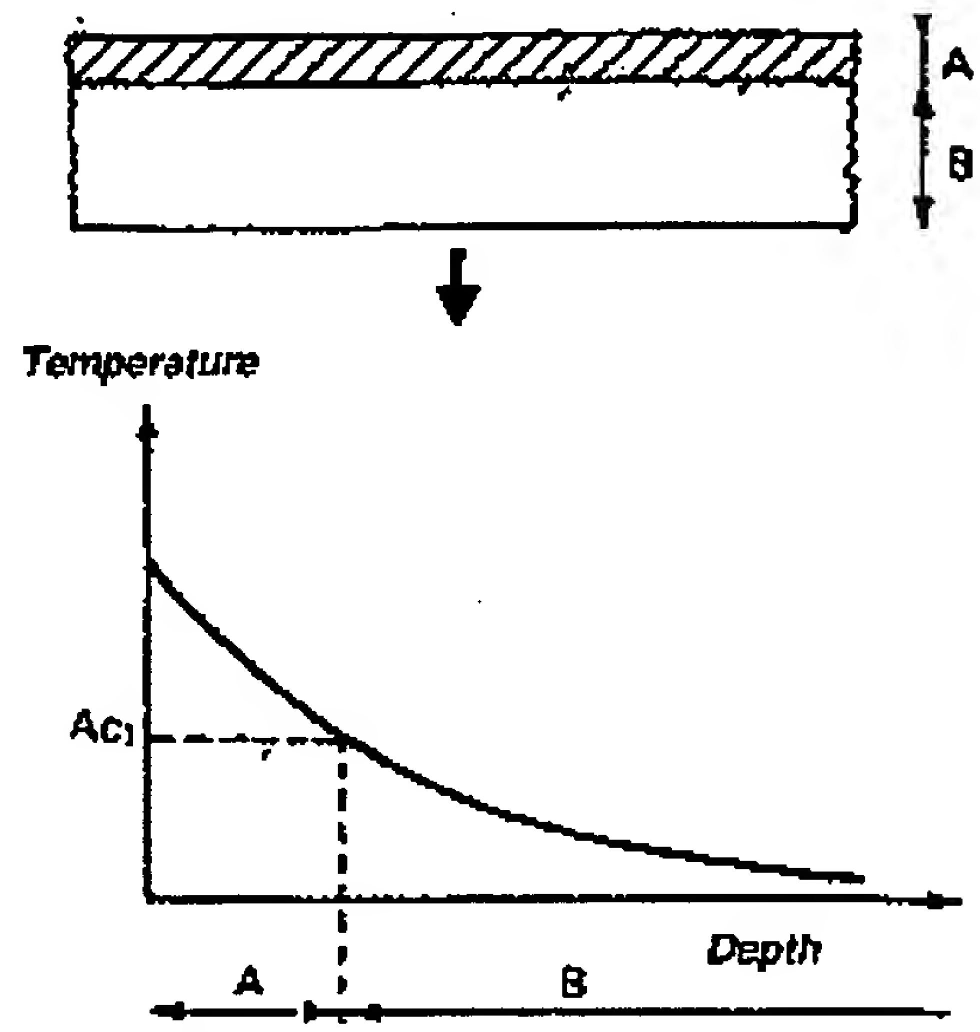
1. Origin of residual stress

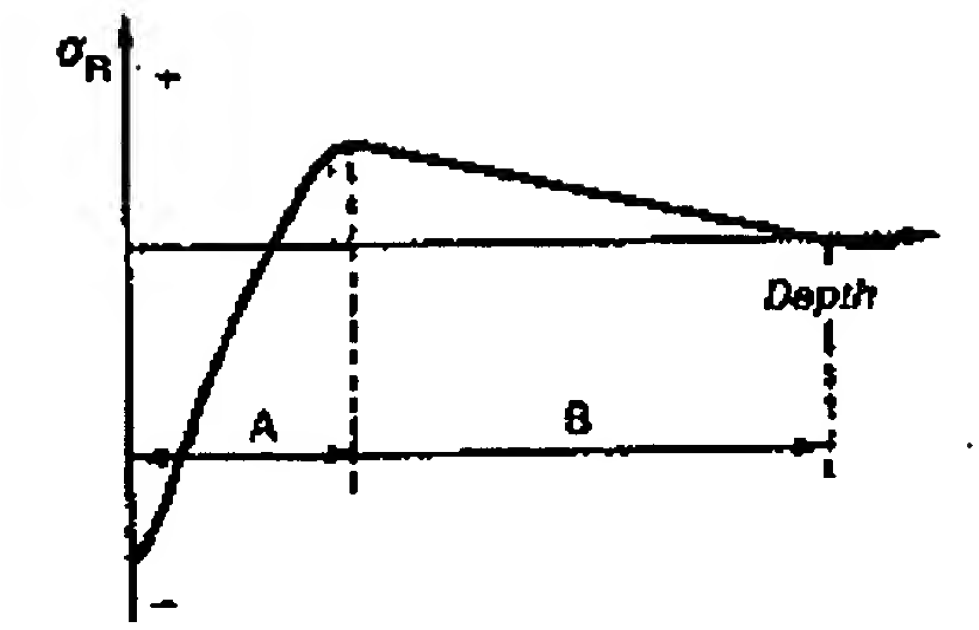


2. a. *Residual stress produced by plastic deformation in the absence of heating*



2. b. *Residual stress resulting from exceeding the elastic limit after the presence of a temperature gradient*





Into A, the temperature is over the phase transformation temperature

2. *c. Residual stress resulting from a change of metallurgical phase*

In general, macroscopic residual stress can be due to the following:

- non-homogeneous plastic flow under the action of external treatment (shot-peening, autofretting, roller burnishing, hammer peening, shock laser treatment),
- non-homogeneous plastic deformation during non-uniform heating or cooling (ordinary quenching, moulding of plastics),
- structural deformation from metalworking (heat treatment),
- heterogeneity of a chemical or crystallographic order (nitriding or case hardening),
- various surface treatments (enamelling, nickel-plating, chrome-plating, PVD and CVD coating),
- differences in expansion coefficients and mechanical incompatibility of the different components of composites (composites with a metallic and organic matrix, ceramic coatings).

Table 1 shows the different origins of residual stress for metal working operations usually carried out in the industry. To produce an industrial part, we can use one or several of the techniques listed in the table. To calculate the residual stress existing in a part, the source of the stress must be identified first.

ORIGIN / **PROCESS**	**MECHANICAL**	**THERMAL**	**STRUCTURAL**
Smelting Casting	No	Temperature gradient during	Change of phase

	; ,	cooling	
Shot-peening Hammer-peening Roller burnishing Shock laser treatment Bending Rolling Chasing Forging Straightening Extrusion	Heterogeneous plastic deformation between the core and surface of the part	No	No
Grinding Turning Milling Drilling Boring	Plastic deformation due to the removal of chips	Temperature gradient due to heating during machining	Change of phase during machining if the temperature is sufficiently high
Quenching without a phase change	No	Temperature gradient	Non
Surface quenching with a phase change (induction, EB, laser, plasma, classical methods)	No	Temperature gradient	Change of volume due to a phase change
Case-hardening Nitriding	No	Thermal incompatibility	New chemical component with Δ V
Welding	Flanging	Temperature gradient	Microstructural change (HAZ)
Brazing	Mechanical incompatibility	Thermal incompatibility	New phase at interface
Electroplating	Mechanical incompatibility	Mechanical incompatibility	Composition of plating depending on bath used
Hot spraying (plasma, laser, Jet Kote)	Mechanical incompatibility, micro-cracking	Thermal incompatibility, temperature gradient	Change of phase in plating
PVD, CVD	Mechanical incompatibility	Mechanical incompatibility	Change of phase
Composite	Mechanical incompatibility	Mechanical incompatibility	No

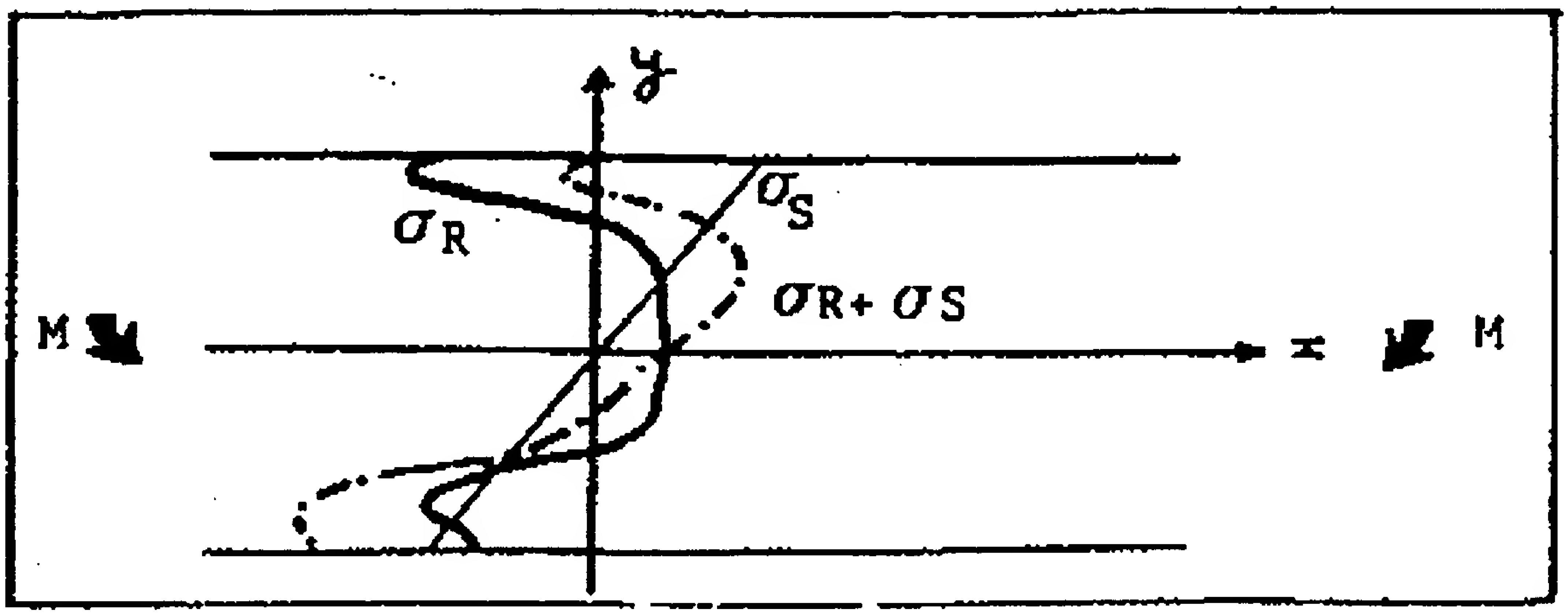
Tableau 1. Main origins of residual stress resulting from different manufacturing processes

EFFECT OF RESIDUAL STRESS ON THE MECHANICAL STRENGTH OF MATERIALS

General

When a part is subjected to a field of elastic residual stresses characterised by a tensor σ_R, on which is superposed a

field of service stresses defined by the tensor σ_S, the real stress to which the part is subjected will be characterised by the tensor $\sigma_R + \sigma_S$ (Figure 3). If the residual stresses are added to the service stresses (residual tensile stress, for example), the part will be locally overloaded due to residual stress. If, on the contrary, an appropriate finishing operation (shot-peening, roller burnishing, for example) is used to introduce residual compressive stress, the part will be relieved of some of the load locally and the mechanical performance of the materials will be increased as a result.



1. *Superposing of residual stress and service stress*

Figure 4 shows the properties of materials which are influenced by residual stress. In the following sub-chapter, we will give several quantitative examples of the effect of residual stress.

2. *Effect of residual stress on the performance of materials*

Influence on the fatigue strength (initiation crack phase)

Residual stress plays an extremely important role with respect to the fatigue strength of materials. It can be considered to be a mean or static stress superimposed on the cyclic stress. As the mean stress σ_m increases, the fatigue strength decreases. This is demonstrated in the Haigh and Goodman diagrams.

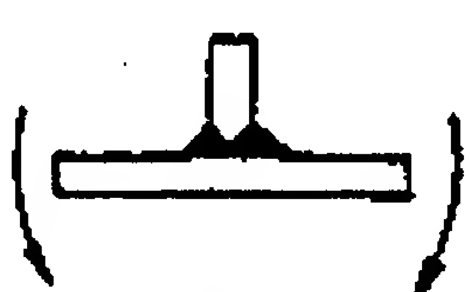
Quenching treatment, after induction heating, introduces very high residual compressive stress into the hardened layer, which results from the increase in volume of the martensitic structure with respect to the ferrito-perlitic structure (this applied to the treatment of annealed steel, for example). In induction quenched cylindrical bars, the residual stress on the surface usually leads to a tangential residual stress equal or slightly greater than the longitudinal stress. The thickness of the material subjected to residual compressive stress is in the same order of magnitude as the layer transformed during treatment [3]. Fatigue tests were carried out by CETIM [4] on 36 mm diameter XC42 steel cylindrical bars, quenched after induction heating, and subjected to repeated bending stress. The results obtained are presented in table 2. It can be seen that the higher the residual compressive stress, the greater the fatigue strength. The resulting gain in fatigue strength produced by the residual stress can be as much as 50% of the fatigue strength of the base material treated.

Type of treatment	Type and depth of treatment at 45 HRC	Surface hardness (HRC)	Fatigue limit after 5.10^6 cycles (MPa)		Residual stress stabilised at the fatigue limit (MPa)	
			σ_m	σ_a	Longitudinal stress	Transverse stress
B	induction 2.7 mm	55-56	596	584	-128 -243	-468 -571
C	induction 4.2 mm	55-56	623	610	-273 -341	-583 -676
D	induction 4.7 mm	54-59	670	660	-655	-603
E	Water-quenched after through-heating without stress-relieving annealing 3.5 mm	60-61	780	750	-863 -777	-1132 -1156

Tableau 2. Effect of quenching and residual stress on the fatigue strength [4]

Figure 5 shows the effect of residual stress on the fatigue strength of welded HLE(E690)[S] steel joints. Three cases are show here: as welded (residual tensile stress), stress-relieved (no residual stress) and shot-peened (residual compressive stress). A marked increase in the fatigue strength was observed in the case of shot-peening.

Fatigue Life test results (r=0,1)

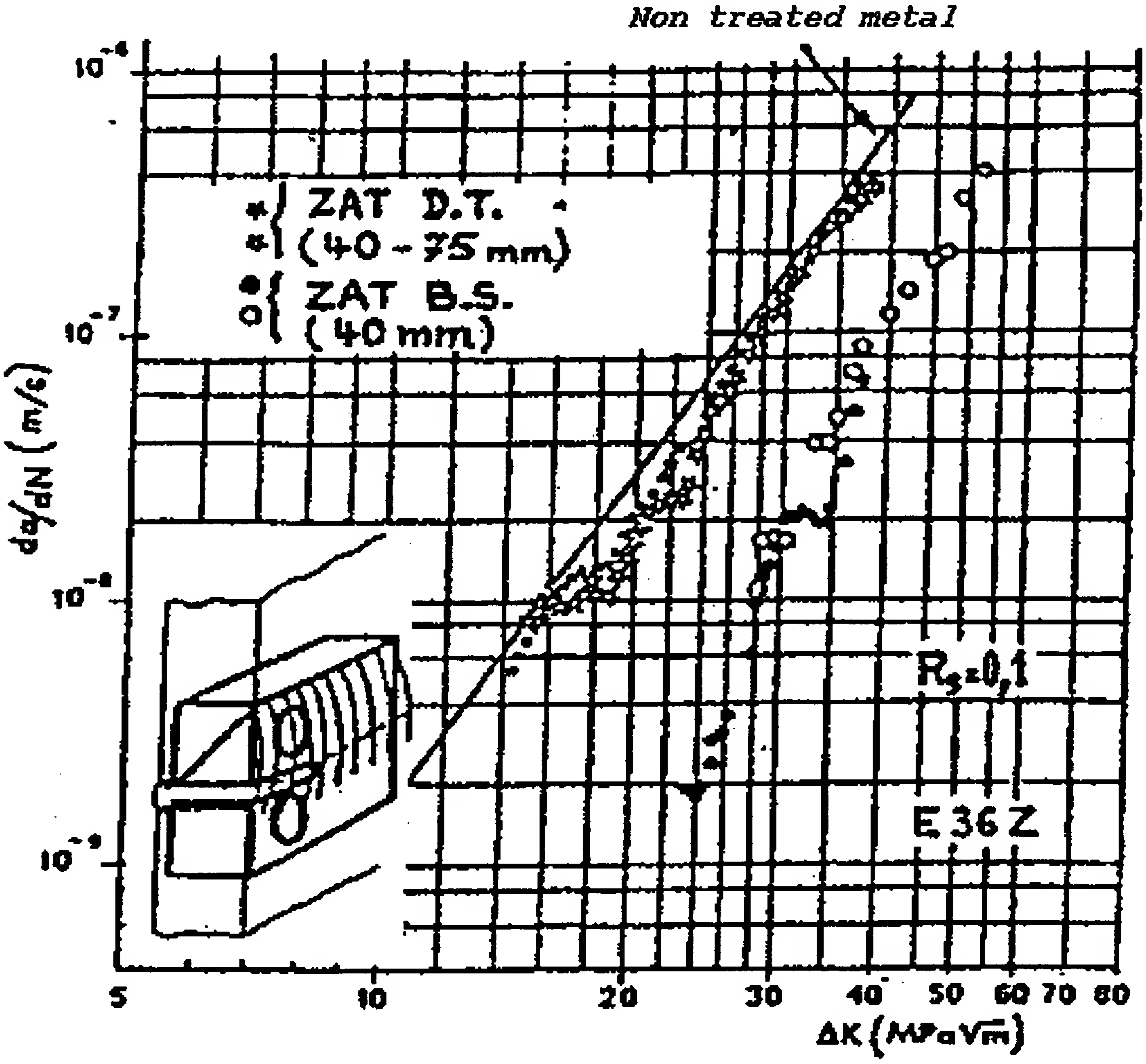
Sample type	State	$\sigma_2.10^6$ (MPa)	σ_{BX} (MPa)	σ_{BI} (MPa)	crack initiation site
 1 Multipasse	BS	207	- 40	+ 23	Base of welded joint
	DT	207	- 37	+ 18	
	TIG	360			
	GP	392		- 519	

1. *Effect of residual stress on the fatigue strength of E690 welded joints [5]*

Influence on fatigue failure (propagation phase) and sudden failure ([6] and [7])

In the case of welded assemblies, the presence of welding defects at the weld toe and the geometric profile of the latter, generally lead to a limited period of crack initiation. The cracking phase must be considered by taking into account the residual stress field induced by the welding operation.

The decisive influence of the residual stress field on the crack propagation speed has been demonstrated in [6]. Figure 6 shows the results of cracking as a function of the residual stress. Relieving residual stress by heat treatment changes the crack propagation speed considerably when the stress is high.



1. *Effect of a residual stress-relieving treatment on the cracking speed in the HAZ (butt-welded assembly of an E36Z steel)[6]*

In the case of a brittle fracture, cleavage starts in a grain when the local stress reaches a critical value of σ_f^* and it generally propagates without difficulty in the adjacent grains by producing a brittle fracture. The tensile residual stress $\sigma_{r,}$ in addition to the applied stress σ , initiates this type of failure for low loads, such that:

$$\sigma + \sigma_r = \sigma_f^*$$

Once cracking has been initiated, the applied stress alone can be enough to allow propagation to continue at a high speed. Failure is therefore very sudden. Residual stresses which facilitate the initiation of brittle fracture by cleavage are therefore very dangerous for steels under load at low temperature. This is why the stress-relieving of welded joints is also recommended.

Grain slips come up against inclusions and create concentrated stresses at their interface which leads to fracture of either the interface or the inclusion. Cavities then appear for a critical initiation stress and grow by plastic deformation of the matrix until their coalescence leads to ductile fracture at least on a microscopic level. The speed at which the cavity grows is not only proportional to the plastic deformation speed but also to the degree of triaxialness of the stresses and to the ratio of the mean stress to the ultimate stress. Coalescence is a plastic instability phenomenon which

no doubt occurs for a critical cavity size. Tensile residual stress not only facilitates the initiation of cavities but, by increasing the mean stress, also accelerates growth. These two effects combine to decrease the critical elongation of ductile fracture. However, this is only important if the ductility is already very low in the absence of residual stresses, since plastic deformation can eliminate them.

Effect on stress corrosion ([8]-[10])

Stress corrosion is a mechanical and chemical cracking phenomenon which can lead to failure under the combined effect of tensile stress and a corrosive environment. Cracking is generally transcrystalline and can appear on all types of materials such as aluminium alloys, steels, copper, titanium and magnesium. The introduction of residual compressive stress can considerably increase the fatigue life of parts subjected to stress corrosion. Tests carried out on magnesium test specimens placed under stress in a salt solution gave the following results

- Ground test specimen: failure after two minutes
- Shot-peened test specimen: no cracking after 12 days under the same conditions..

The tests conducted by W. H. FRISKE show that the fatigue life is 1000 times greater for a shot-peened 304 grade stainless steel part than it is for a non-shot-peened part [9]. Tests carried out by CETIM on Z6CN18.9 stainless steel produced similar results [10].

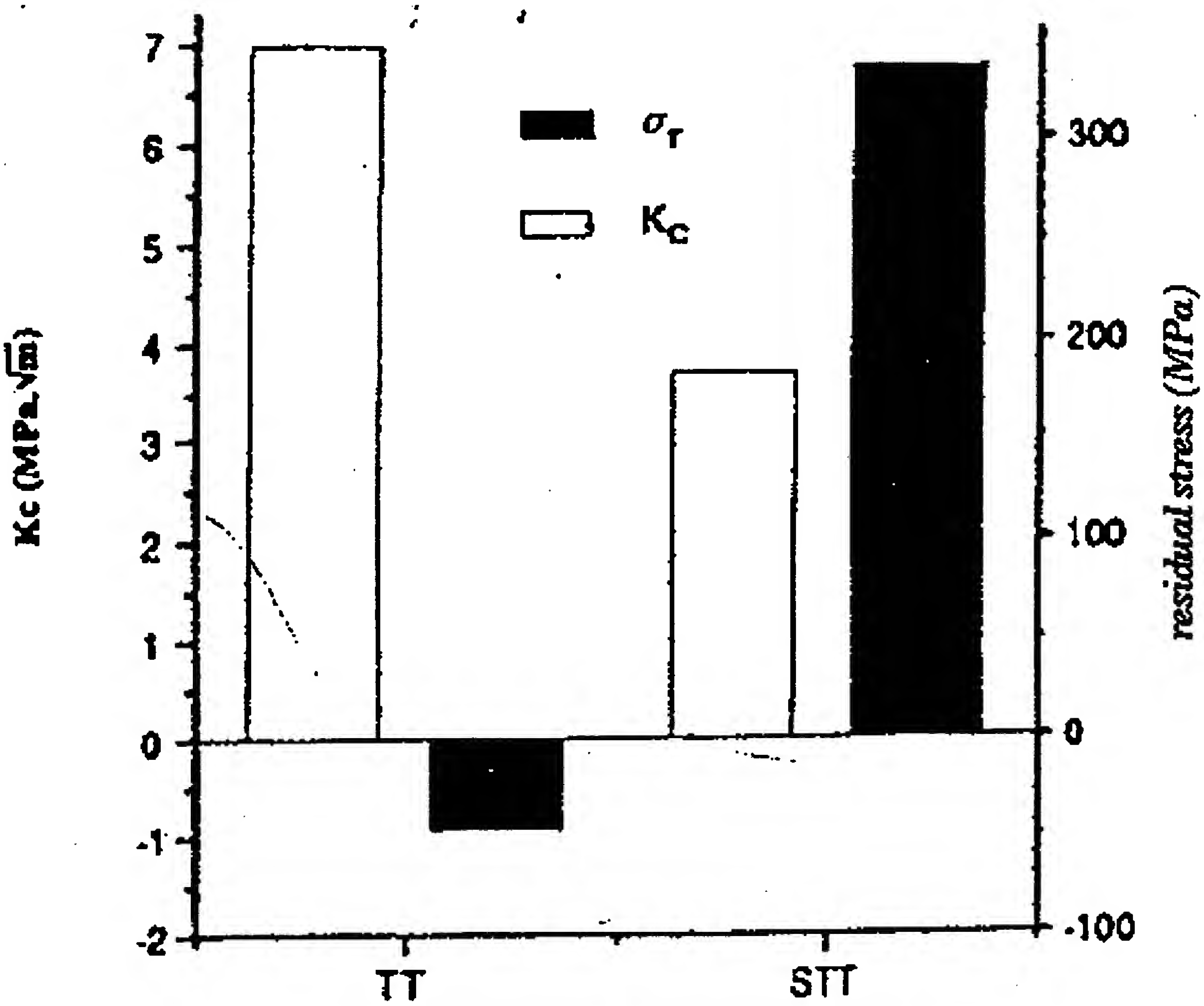
Effect on adhesion of coatings [11]

Most coatings are produced for a specific reason, particularly to improve the corrosion and wear resistance of the base material, or to provide a thermal barrier for use at high temperature. But this is only achieved if the coating adheres to the substrate correctly. Adhesion therefore indicates correct preparation of the surfaces to be coated and the quality of the coating operation. The last few years have seen the appearance of plasma spraying techniques, both at atmospheric pressure and at reduced pressure. These processes offer high degree of flexibility for coatings in critical areas. However, high residual stress, inherent to the coating method used, can remain in the coatings and in the substrates. They are of several types: microstresses in the grain, produced during cooling, and macrostresses affecting the entire coating. Macrostresses are created not only by cooling but also by the difference in temperature between the substrate, the sprayed layer and the outside surface. The differential contraction thus produced between the various materials, due to the difference in physical and mechanical properties, determines the stresses in the coating and the coating/substrate interface. These stresses therefore influence the mechanical and thermomechanical behaviour of the coated parts.

In order to appreciate the quality of a coating, three types of damage to parts in service can be considered:

- The coating deteriorates rapidly,
- The properties of the substrate are modified by the coating,
- The damage is common to both materials. It is located at the interface and jeopardises both the adhesion and the fatigue life.

C. RICHARD et al.(12] have shown that decreasing the residual stress by thermal treatment of the coating considerably improves adhesion at the interface. Figure 7 illustrates the effect of residual stress. It can be seen that the apparent toughness of the interface is improved by 100% when heat treatment is applied. There is a high level of residual tensile stress in the test specimen without heat treatment. When the level of residual tensile stress increases, the true toughness of the coating decreases. An increase in the residual compressive stress produces the opposite effect.



1. Influence of heat treatment on the residual stress and the toughness of the interface: case of plasma sprayed coatings at atmospheric pressure

Influence of residual stress on the tensile strength, friction, wear and dimensional stability

The effect of residual stress on the tensile strength is obvious, particularly in structures made of composite materials or when the prestressed layer is very thick compared with the thickness of the parts. In composites, residual stress is produced as a result of the thermal and mechanical incompatibility of the reinforcements and matrix. This can influence the macroscopic properties of composites under tensile or compressive stress [12].

Little research has been carried out on the effect of residual stress on friction and wear properties. Their role is often masked by other parameters. The increase of hardness during treatment and changes in the toughness and adhesion of anti-wear coatings due to residual stress can considerably affect the resistance to friction. Up until the present, this effect has been integrated into the global parameter of adhesion. In the future, work will be carried out to try to determine the real effect of residual stress.

The problem of dimensional stability has been known for a long time. When a part is machined that contains residual stress produced by heat treatment or welding, the shape of the part can change after operation due to the relaxation of residual stress. This is why stress-relieving treatments are frequently used to avoid this type of defect. Reference [13] gives a very methodical approach to defining the criteria and processes relating to relieving stress in welded structures. The same type of reflection can be applied to other types of parts.

TAKING RESIDUAL STRESS INTO ACCOUNT WHEN CALCULATING THE EXPECTED FATIGUE LIFE

Introduction

In the above discussion, we have mentioned the different effects of residual stress on the mechanical strength of structures and materials. Although, today, we are just starting to be able to quantitatively estimate the fatigue life taking residual stress into account, it is still too early to extend these predictions to other types of stress which are far more complex and involve physical and chemical phenomena. Statistics show that failures of a purely mechanical origin are mainly due to fatigue. It is for the reasons indicated above that this article only addresses problems concerning the prediction of fatigue life. Two other articles (H. P. Lieurade and A. Pellissier-Tanon) in this collection deal with the question of predicting the effect of residual stress on cracking. Although they concern welded structures, the concepts developed in these two articles can be applied to other types of structures. By limiting our approach to prediction of the fatigue life to the fatigue cracking initiation stage, we can analyse the problem of predicting the fatigue life of mechanical components subjected to a large number of cycles.

Calculating the effect of residual stress on the fatigue strength

Based on the experimental results mentioned above (4.2), it would seem that a linear relationship of the Goodman type can be used to take residual stress into account:

$$\sigma_a = \sigma_D - \frac{\sigma_D}{R_m}(\sigma_m + \sigma_R)$$

where

- σ_a is the amplitude of admissible stress

- σ_m is the mean fatigue stress

- σ_D is the purely reverse tensile fatigue limit

- R_m is the true rupture strength

- σ_R is the residual stress measured in the direction of the applied service stress

The numerous studies mentioned in reference [14] show that the effect of residual stress is greater when the properties of the materials are high.

If we try to represent the development of σ_a according to the residual stress σ_R by an equation of the following type

$$\sigma_a = \sigma_D - \alpha \times \sigma_R$$

the experimental results generally show that α increases with the strength of the material; for example, in the case of machining stresses in an XC38 grade steel, Syren et al. find the following:

$\alpha = 0$ in the annealed state

$\alpha = 0.27$ when quenched and tempered

$\alpha = 0.4$ when quenched

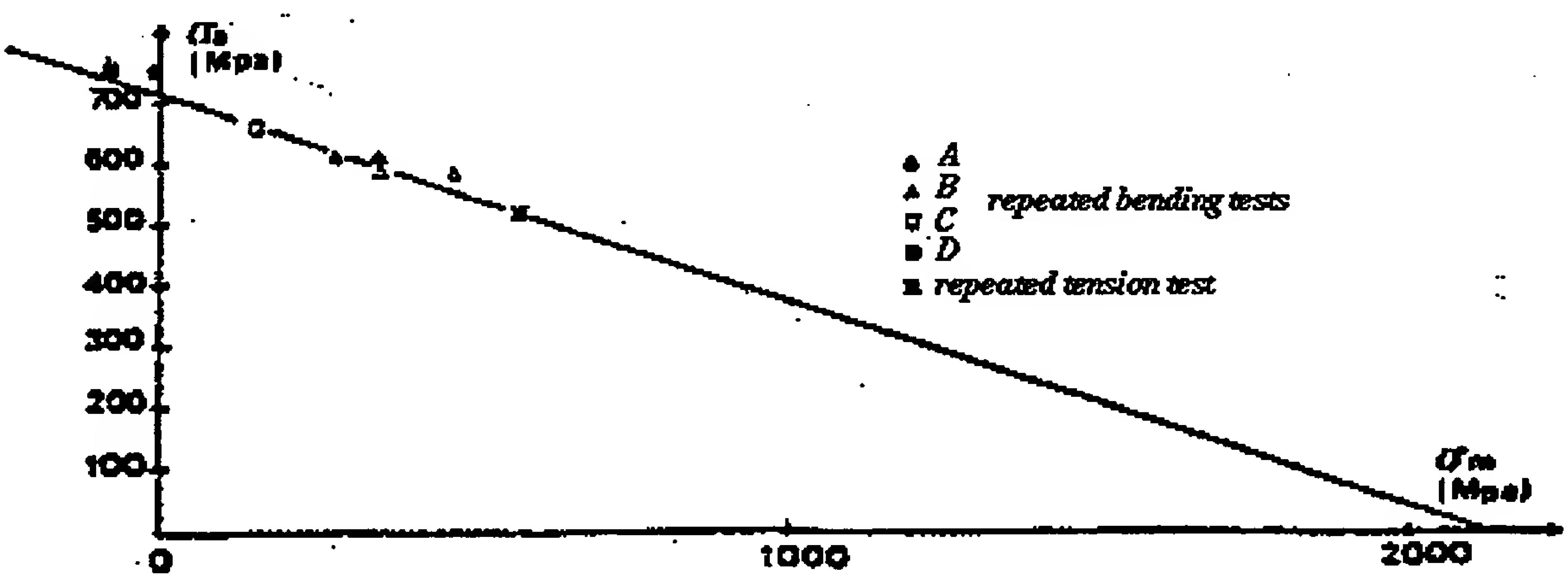
Unfortunately, these results are in contradiction with an equation of the Goodman type. In equation (2), the coefficient α is none other than what is usually called the endurance ratio:

$$\alpha = \frac{\sigma_D}{R_m}$$

And we know that this parameter decreases as the rupture strength of steels increases.

This apparent contradiction is probably explained by the fact that the residual stress relaxation phenomenon has not been taken into account. The value of the residual stress σ_r to be introduced into equation of type (1) or (2) above, must correspond to the stabilised fatigue stress, or the coefficient of influence will include the relaxation process. References [15] and [16] provide further information on the relaxation mechanism of residual fatigue stress. However, Syren's results show that relaxation is much greater when the mechanical properties are lower.

When the above experimental results are used with the residual stress measured after carrying out a fatigue test, and therefore stabilised, it is sometimes possible to use a type (2) equation. In the case of the fatigue bending test on cylindrical XC42 steel bars quenched after induction heating (table 2), the fatigue test results for the different treatments correspond perfectly to the Haigh diagram, provided any possible influence of transverse residual stress on the fatigue stress is ignored (Fig. 8).



1. *Use of Haigh diagrams to take longitudinal residual stress into account (XC42 steel quenched after induction heating)*

It is not possible, however, to extend these results to all materials and to the different manufacturing processes which introduce residual stress. Also, preliminary tests are needed to validate the methodology.

The use of residual stress in calculations based on endurance diagrams of the Haigh or Goodman type usually only allows for an estimation of the increase in fatigue strength as a function of the residual stress.

Secondly, this approach only allows for the combination of uniaxial stresses. Yet the residual stresses produced by the

various manufacturing methods used to make the part are always multiaxial. The stresses on the surface are biaxial while those inside the part are triaxial. Depending on the area in which the fatigue crack is initiated (on or below the surface), the bi- or triaxial stresses need to be included when calculating the fatigue life. This raises the problem of choosing a multiaxial fatigue stress criterion. A simplified approach based on an endurance diagram can therefore only be an approximation.

Experience shows [4] that the traditional Mises and Tresca criteria can only be used in the presence of higher mean or residual stress. In this case, if is preferable to use criteria which include the amplitude of octahedral shearing (τ_{oct}) or the maximum shearing (τ_a) max and maximum hydrostatic pressure (P_{max}), as indicated below:

$$\tau_{alt} = f\left(A, B\, P_{moy}, C\, P_{alt}\right)$$

hms (hydrostatic mean stress) à mettre à la place de "moy" dans le formule

An example can be given by the equation below:

$$\tau_{alt} = A + B\,P\frac{D}{moy} + C\,P\frac{E}{alt}$$

A, B, C, D, E are material constants.

If $\Delta\tau_{alt}$ is taken on the maximum shearing plane, D = E = 1, and B = C and we have the Dang Van criterion [17].

If $\Delta\tau_{alt}$ is taken on the octahedral shearing plane, when D = E = 1 and B = C and we have the Crossland criterion [18], when D = E = 1 and C = 0, we have the Sines criterion [19], and when D = E = 1 , and B ≠ C , we have the Kakuno criterion [20].

This type of development can be continued to invent new "criteria", but it leads to complications because of the increasing number of parameters which need to be determined. Even with a linear relationship of the Dang Van type two Wöhler curves have to be determined to obtain at least the two points needed to produce the diagram. If additional constants are added, the test plane will be even greater which means that the criterion cannot be used in industry. As a result, the criterion to be used must be simplified as much as possible. In our case, we are dealing with radial loading problems $\left(\sigma_1 = K_1\ \sigma_2 = K_2\ \sigma_3\right)$ and a relationship of type (3) is sufficient. To simplify matters further, we can use the Crossland or Dang Van criterion. In the case of combined and out-of-phase loading, new criteria have been developed to take the out-of-phase effect into account [21]-[23]. But at yet, these criteria have not been validated in a study in which combined and out-of-phase residual stresses have been taken into account. When the fatigue stress is complex, it is also very difficult to calculate the expected residual stress relaxation.

When fatigue cracks are initiated on the surface, the stresses to be taken into account are biaxial; this gives the following for the Crossland or Dang Van criterion:

$$\tau_{octa} = \frac{\sqrt{2}}{3}\left(\sigma\frac{2}{1a} + \sigma\frac{2}{2a} - \sigma_{1a}\,\sigma_{2a}\right)$$

$$\tau_a = \frac{\sigma_{1a}}{2}$$

$$P_{max} = \frac{1}{3}\left(\sigma_{1a} + \sigma_{2a} + \sigma_{1m} + \sigma_{2m} + \sigma_{1R} + \sigma_{2R}\right)$$

where

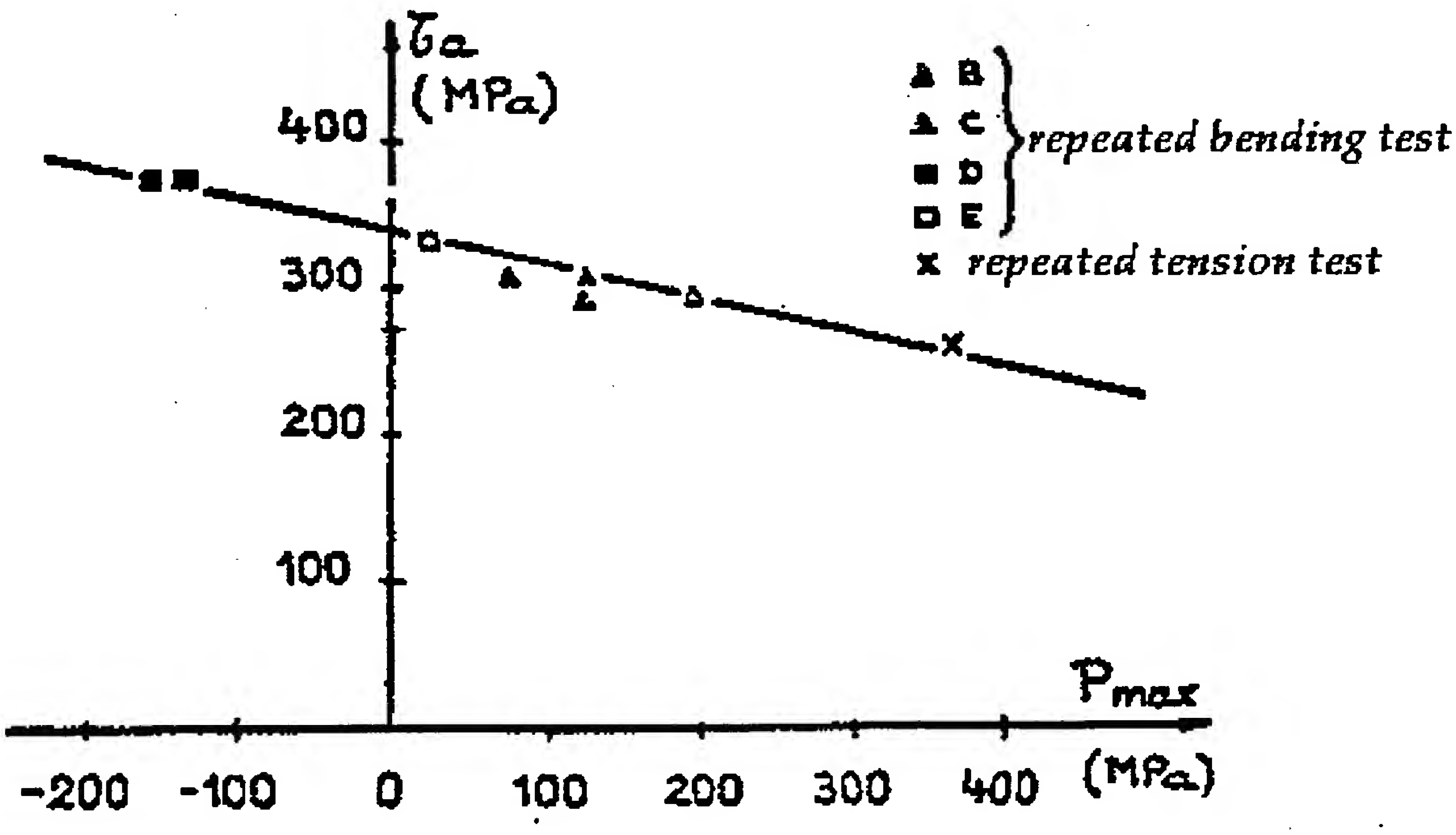
- σ_{1a}, σ_{2a} represents the amplitude of the main reversed fatigue stresses $(\sigma_{1a} > \sigma_{2a})$

- σ_{1m}, σ_{2m} represents the average value of the main fatigue stresses

- σ_{1R}, σ_{2R}

are the residual stress values measured in the two main directions (stabilised values).

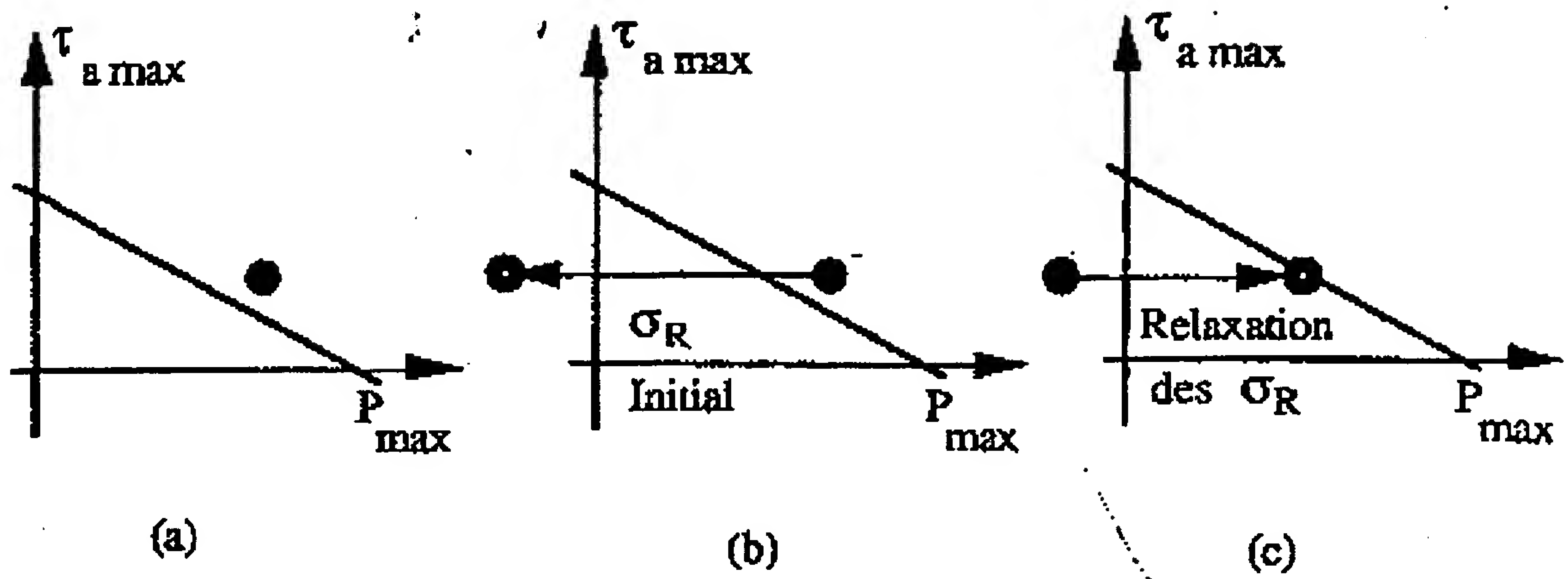
To use the multiaxial fatigue criteria, the reference curve for the material being considered is needed, just as it is when using the Goodman or Haigh diagram. Reference [4] shows that the use of Crossland or Dang Van criteria takes the increase in the bending fatigue strength into account perfectly as a function of the residual stress introduced by the various treatment conditions (figure 9).



1. *Use of the Dang Van criterion to take residual stress into account (XC42 steel quenched after induction heating)*

   When the multiaxial aspect is brought into the picture, the method which consists in introducing residual stress into the calculation in the same way as a mean stress therefore seems to give satisfaction. The whole problem lies in defining the residual stresses to be included in the calculation.

   Taking residual stress into account is essential for correct prediction of the fatigue limit. Figure 10 shows the important role played by compressive residual stress. If it is not taken into account, the fatigue strength is underestimated (fig. 10a). If the residual stress measured or calculated is used without taking relaxation of the residual stress into account, the fatigue strength is overestimated (fig. 10b). The correct method consists in calculating the fatigue strength after taking relaxation into account (fig. 10c).



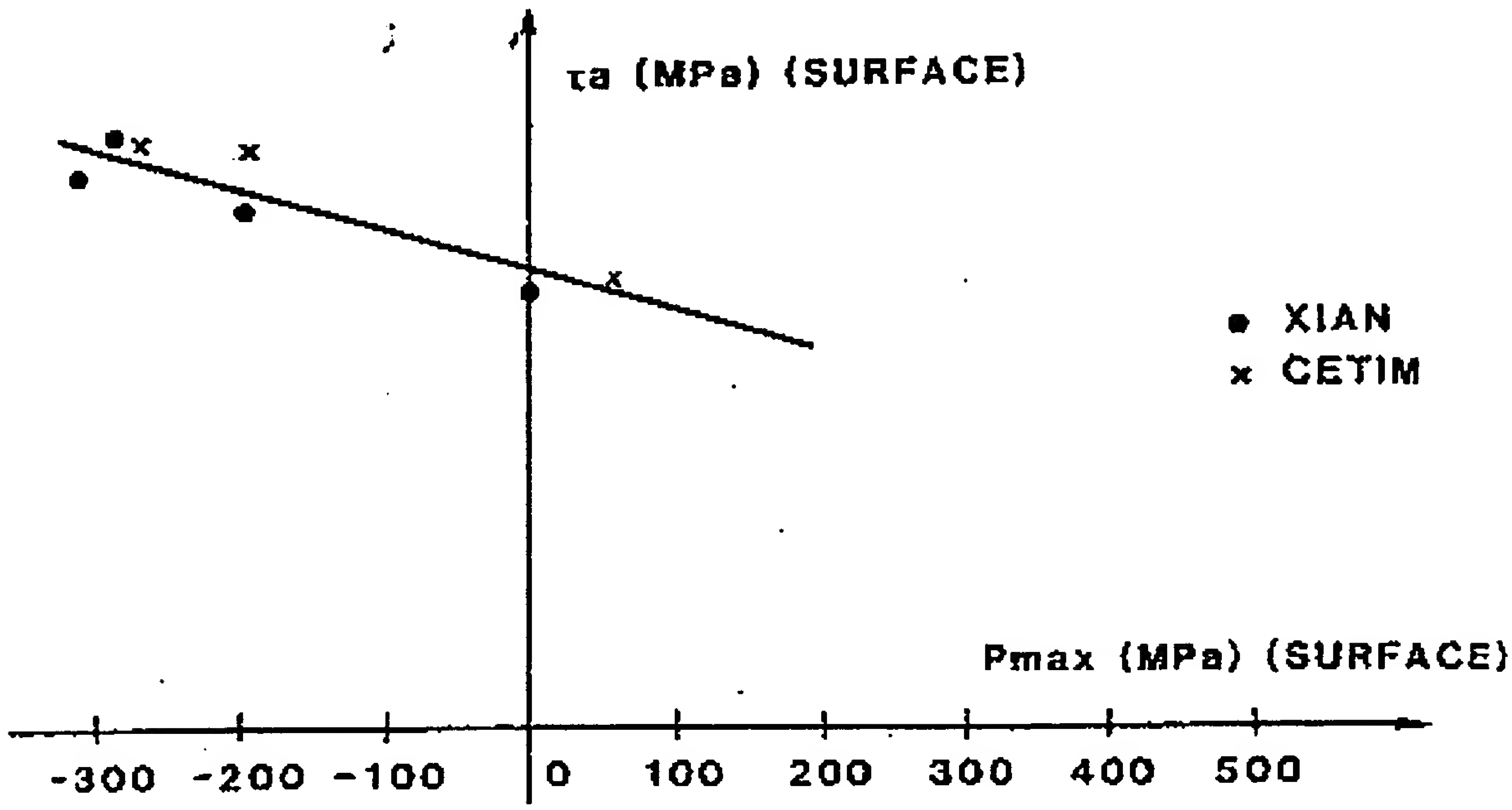
2. *Illustration of the different methods used to take residual stress into account*

In order to correctly evaluate the effect of residual stress, various problems must be solved:

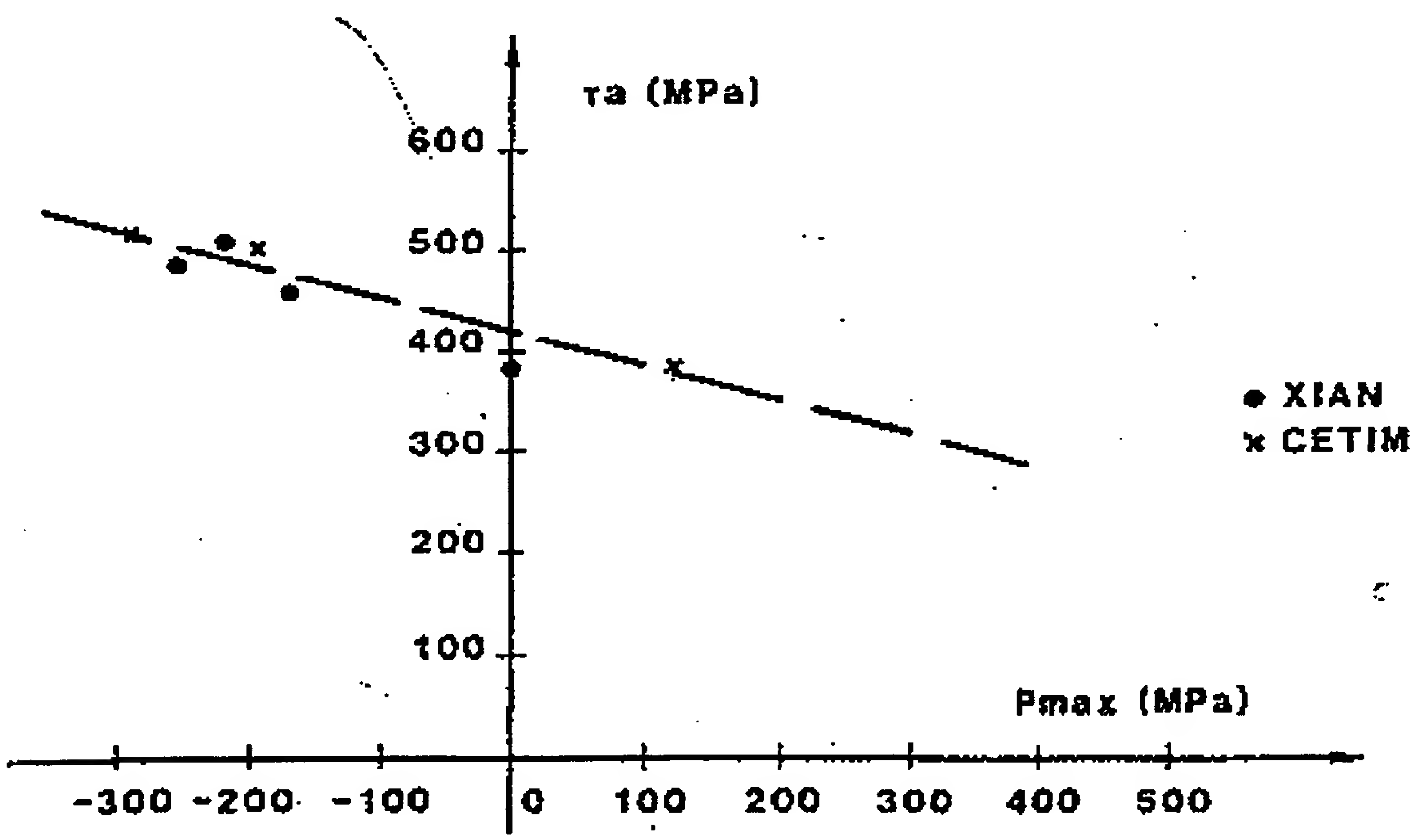
- Measuring methods must be available to determine residual stress in the critical zone. A large range of measuring methods currently exist and it is possible to take measurements in most of the cases studied, particularly as a result of development of the X-ray method [24] and the incremental hole method [25].

- When a complete measurement profile is available of the residual stress in the surface layer in which the fatigue crack is initiated, the profile sometimes has high stress gradients. It is then difficult to know what stress value to choose – the surface stress or the stress peak which is often slightly below the surface (in the case of shot-peening, for example).

To make a correct calculation, it would be necessary to use calculation methods which take the stress gradient into account and make the calculation not only for a single point but for a sufficient thickness of the material (thickness of critical layer) for it to be representative of the basic volume in which the fatigue damage process occurred [26]. Figures 11 and 12 give an example of processing of the results of [15] (chapter 5). Figure 11 shows the fatigue results on a Dang Van diagram taking both the residual stress and its relaxation into account. A fairly good correlation can be observed. This indicates that a multiaxial fatigue criterion taking the hydrostatic pressure into account can be used to predict the fatigue strength in the presence of residual stress. Since, in this case, the crack initiation zones are below the surface, calculations were made for different critical layer depths. Figure 12 shows the results obtained for a critical layer depth of 100 μm. Better alignment of the experimental points was observed. This example illustrates the possibility of improving the calculation precision by using the critical layer thickness approach. It is particularly relevant in the case of notched parts.



1. Fatigue results for a 45SCD6 steel treated under different conditions in a Dang Van diagram taking the residual stress on the surface into account

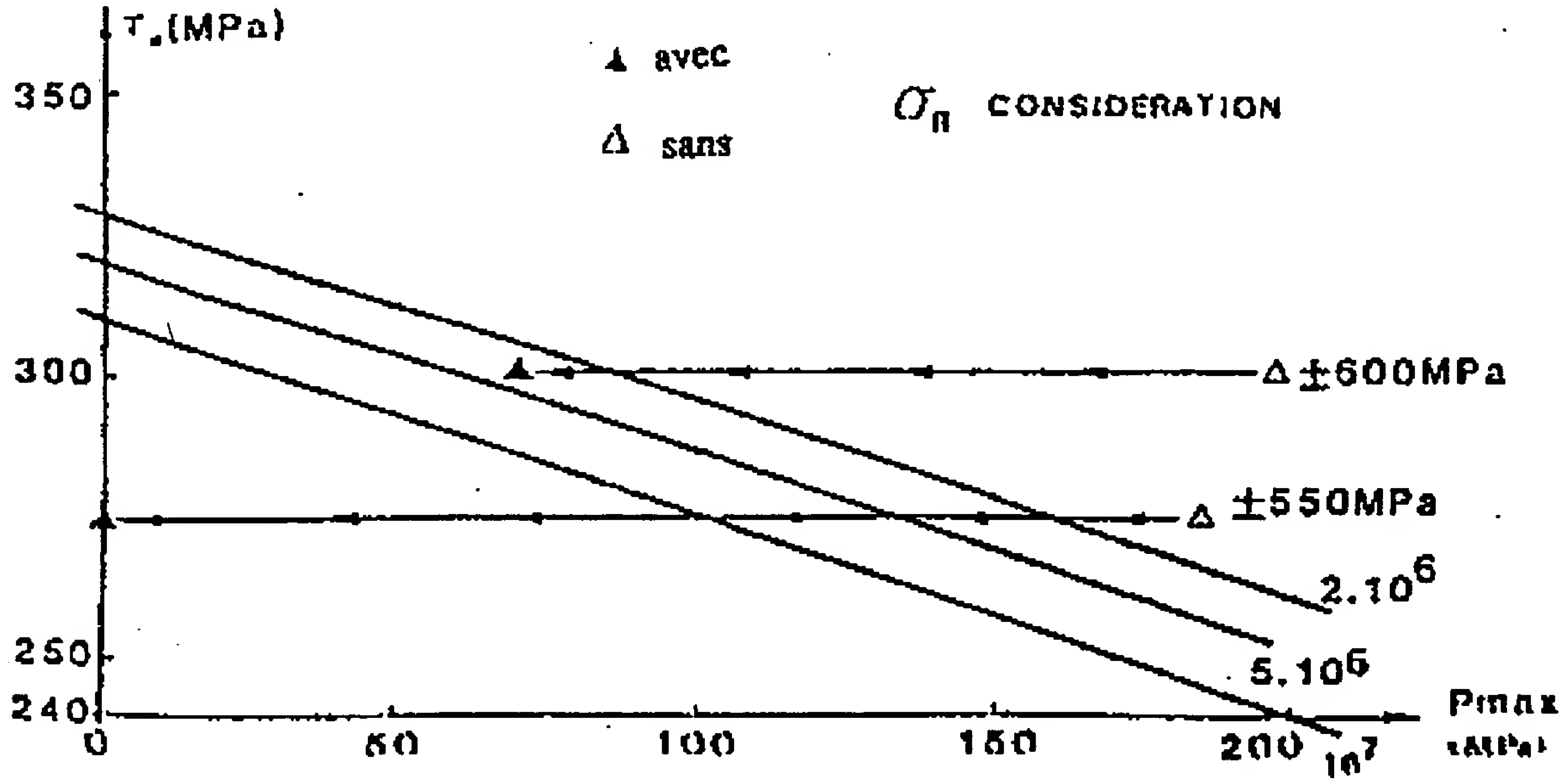


2. Fatigue results for a 45SCD6 steel treated under different conditions in a Dang Van diagram taking the residual stress into account using the "critical layer" approach

It has been known for a long time that residual stresses are not stable when they are subjected to fatigue loading. To calculate the expected fatigue life, precise information is therefore needed in order to introduce stable residual stress values into the calculation presented above, that is, the stress values that are really likely to be present in the part during the best part of its lifetime.

The stress must therefore be measured on a part already under cyclic loading or relaxation of the residual stress estimated according to experience or modelling. In [15] and [16], we presented a complete model using the finite element method to determine the stabilised residual stress after fatigue loading. This estimation of the residual stress can then be used to calculate the fatigue life of a part taking residual stress into account. Despite the initial definition of the Dang Van criterion, which proposes that it only be used in cases of fatigue strength with an unlimited number of cycled, we attempted to extend this criterion to include a limited fatigue life with a very

large number of cycles (more than 2.10^6 cycles) [27]. Figure 13 shows an example of the fatigue life estimated by calculation. First we defined a fatigue strength diagram of the Dang Van type according to the fatigue life obtained from a series of fatigue life contours. We then calculated the residual stress relaxation using the finite element method [15]. Finally we introduced the stabilised residual stress into the diagram. In our example, in the case of a loading of ± 550 MPa, the point corresponding to loading is inside the limit of the fatigue life at 10^7 cycles. No failure occurs.. For a loading of ± 600 MPa, the point corresponding to loading including the residual stress is between the line corresponding to 5.10^6 cycles and that of 2.10^6 cycles. Failure therefore occurs between 2 and 5 million cycles. The tests give an average fatigue life for the above loading in the order of 3.5 million cycles. Our example shows that, if the cyclic properties of the material are correctly known, it is possible to predict the fatigue strength of the material in the presence of residual stress.

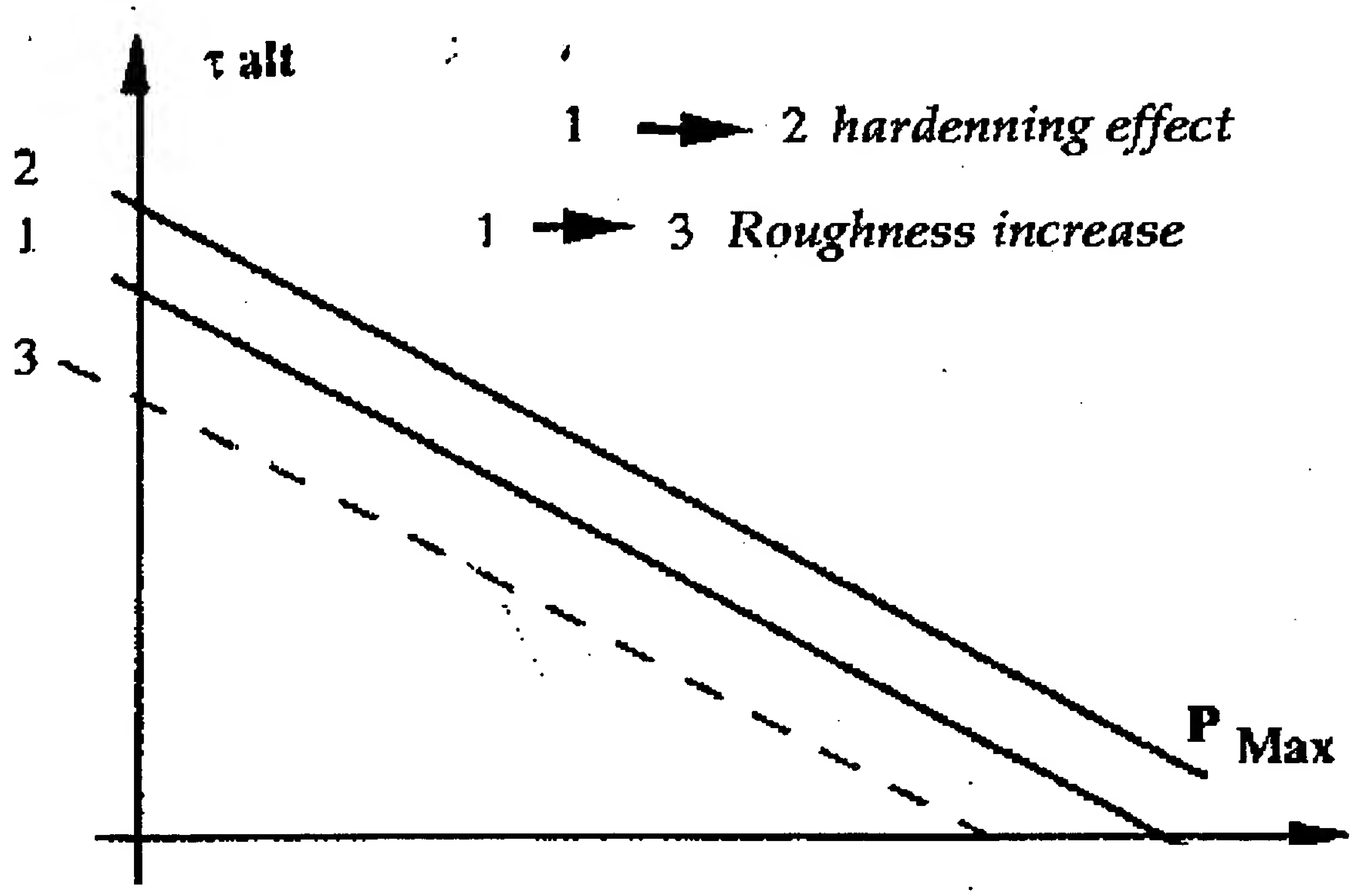


3. *Prediction of the fatigue life using the Dang Van criterion for a shot-peened 35NCD16 steel, without taking residual stress into account.*

However, it should not be forgotten that other factors must also be taken into account in calculating the fatigue life – the introduction of residual stress is often accompanied by other changes in parameters which have an influence on the fatigue strength. In particular, these include:

- a new roughness which changes the local stress concentration,
- additional strain-hardening of the surface due to plasticising,
- a new metallurgical structure of the surface layers.

Figure 14 shows the effect of the surface finish and strain-hardening on the fatigue strength of materials. It can be seen that an increase in the roughness decreases the safety area and strain-hardening increases the safety area provided it does not damage the material.



1. Illustration of the effect of the surface finish and strain-hardening on the fatigue strength

In the case of thermal or thermochemical surface treatments (induction quenching, case-hardening, etc.), for example, it is necessary to take the new fatigue strength of the treated layer into account in the calculation.

The problem is more complex in the case of residual stress introduced by plastic deformation (pre-straining, machining, shot-peening, roller burnishing), since it is more difficult to distinguish between the influence of residual stresses and residual micro-stresses present in the grains of the deformed material, and that of strain-hardening of the material.

Evans [28] made this distinction in the case of shot-peening; to do so, he carried out three types of fatigue tests on materials with various mechanical properties:

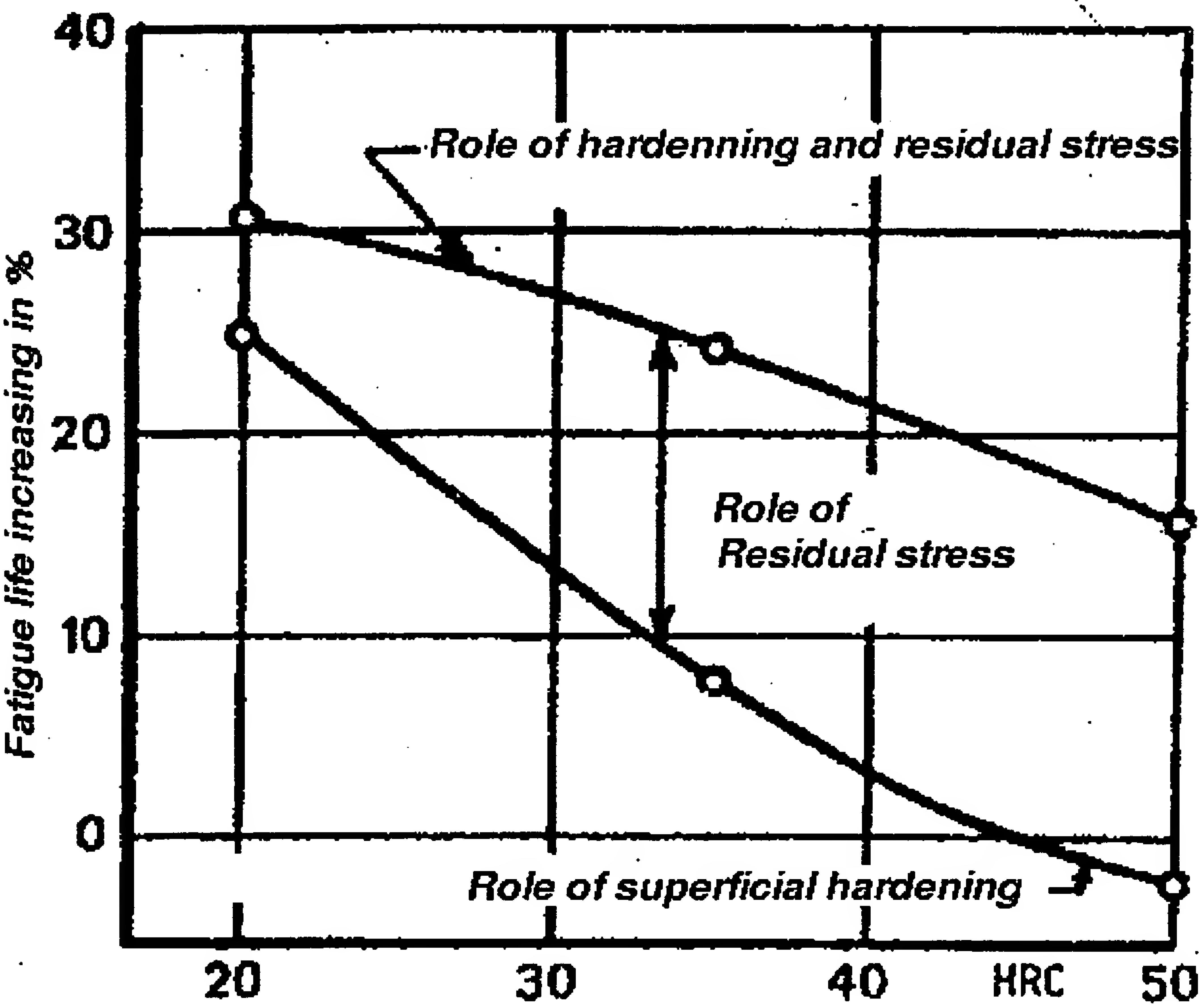
- Fatigue tests on a non-shot-peened material,
- Fatigue tests on a shot-peened material,
- Fatigue tests on a shot-peened material, but with a mean test stress σ_m

which compensated for the surface residual stress. In this type of test, the effect of the macroscopic residual stress is cancelled out and the fatigue strength obtained only depends on the increase in the mechanical properties of the plastically deformed material and the residual microstresses distributed throughout the material. The results obtained are presented in figure 15.

It can be observed that, for materials with low resistance, the increase in the fatigue strength is mainly due to surface strain-hardening. On the other hand, for highly resistant materials, it is mainly the influence of the residual stress which governs the fatigue strength. When materials have low elastic limits, the stresses introduced by shot-peening relax much more easily than they do when the elastic limit is high. This test only shows a general tendency and does not exactly show what the author is trying to demonstrate, since in the two types of tests for the same material, the ratio of $R(\sigma_{min} / \sigma_{max})$ is modified. As we have shown, the residual stress relaxation changes when the R ratio is varied [15].

The real contribution of each factor will therefore be different from that indicated in figure 15.

It can thus be seen that taking residual stress into account in the calculation requires a serious examination of the different parameters involved. When reliable results are needed, fatigue tests will no doubt need to be carried out on the part or the structure concerned. However, modelling enables the variation in the different parameters to be rapidly simulated in order to find an optimum solution.



1. *Effect of the resistance of the base metal on the increase in the fatigue strength after shot-peening treatment, distinguishing between the effect of strain-hardening and that of residual stress*

Partial conclusion

The above results show that it is now possible to take residual stress into account in calculations designed to predict the fatigue life using a global approach. This must take the relaxation of residual fatigue stress into account, as well as the other effects (strain-hardening, hardness) introduced by the manufacturing method used. A multiaxial fatigue criterion which can integrate both the problem of residual stress and the effect of the stress gradient applied to a zone in the presence of stress concentration has been developed i.e. the Crossland or Dang Van criterion. It is used for a stabilised state of residual stress, averaged out for a basic volume of damage (thickness of critical layer), and applied within a network of contours which represents the fatigue life. In the future, tests will be carried out to validate this type of criterion in the case of combined stresses on notched parts in the presence of residual stress.

INCORPORATING THE NOTION OF RESIDUAL STRESS INTO THE DESIGN OFFICE

Incorporating the notion of residual stress into the design office must be gradual and can be divided up into several phases.

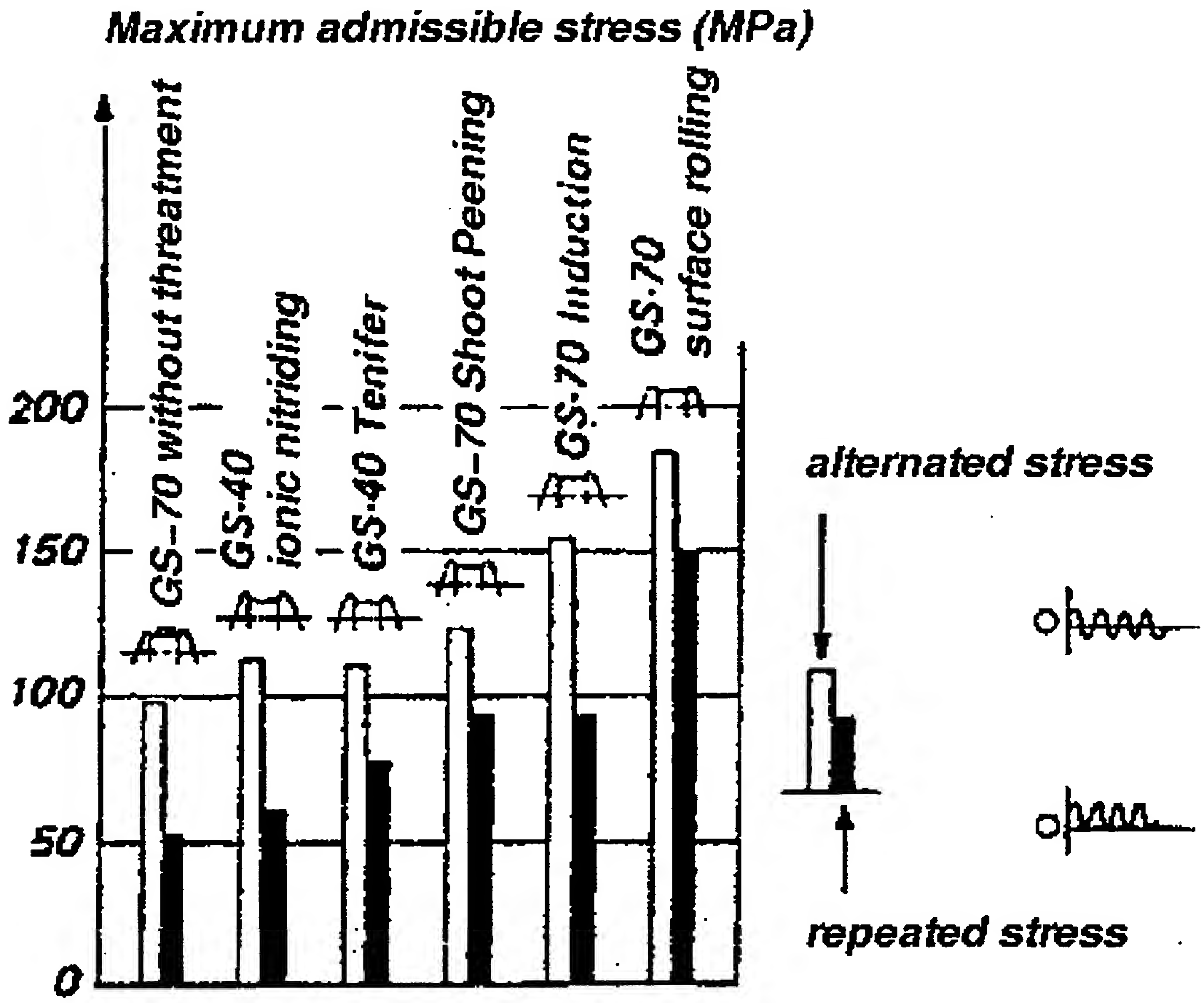
Today, very few industrial sectors consider the "residual stress" parameter directly. In technical specifications, requirements are included which are often closely related to residual stress without actually naming it. An Almen intensity must be guaranteed in the case of shot-peening, for example, a roller burnishing load, a machining procedure or a minimum treated thickness in the case of thermal or thermochemical treatment, and a maximum dimensioning tolerance in the case of a machined or welded part.

In the first phase of incorporation, we can use a semi-quantitative notion to evaluate the increase in performance in terms of fatigue life or fatigue strength. A few examples can be presented. Table 3 gives an example of the effectiveness of shot-peening in increasing the fatigue life of different types of mechanical parts, and figure 16 shows the beneficial role played by roller-burnishing on the fatigue strength of GS cast iron crankshafts. Figure 17 shows a horizontal comparison of gains to be expected in terms of fatigue strength from various surface treatments. The results presented here are not at all exhaustive and are taken from a limited bibliography. However, this figure should not be taken as a reference, since the geometry of the test specimens differs for each type of treatment. In certain cases, this parameter can have a important effect on the gain achieved. Each industrial sector must carry out this type of comparison for the treatments and materials used in order to help engineers design their products more effectively.

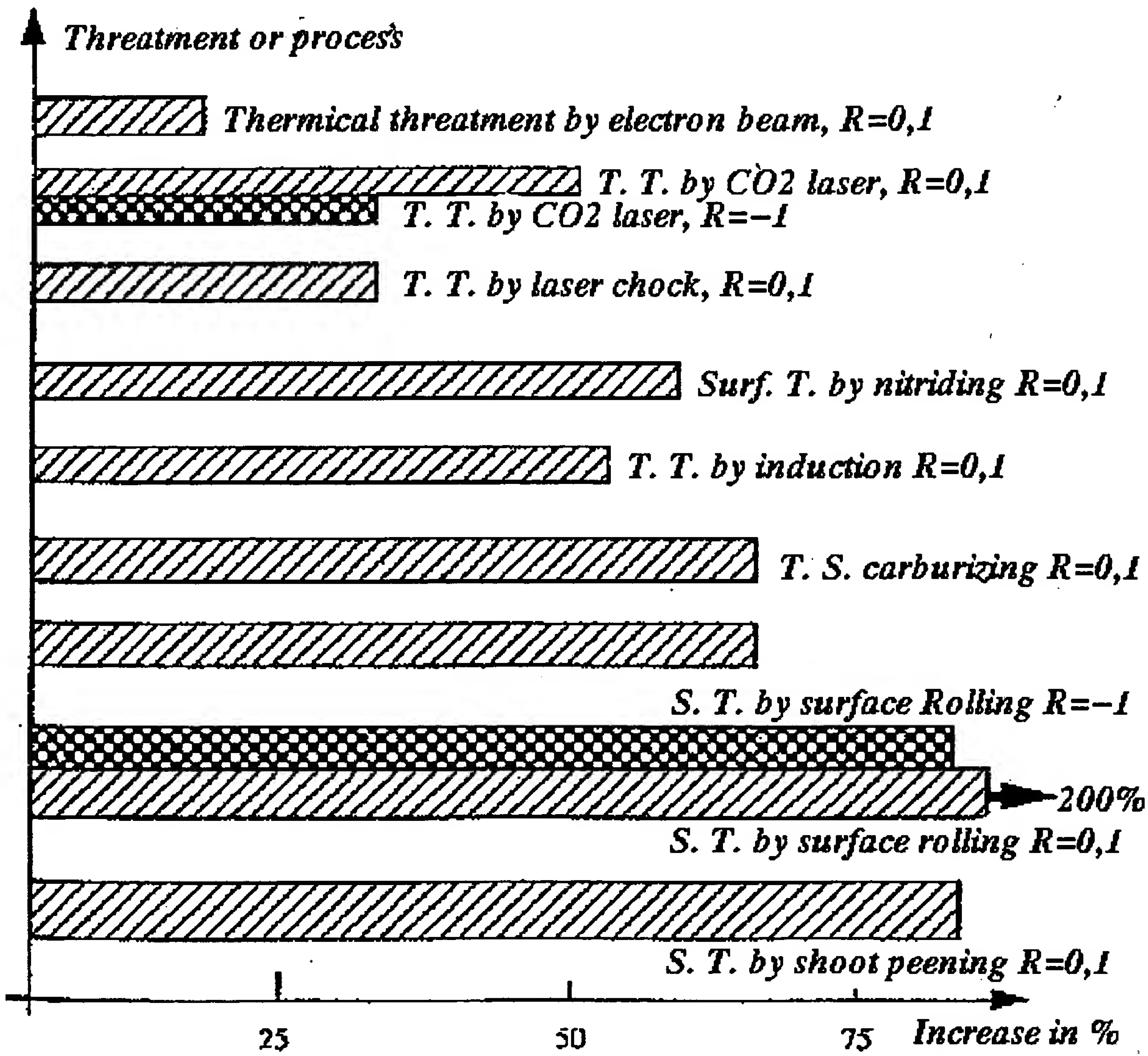
Type of part	Type of stress	Increase in the fatigue life (in %)
Spindles	Reverse bending	400 to 1 900
Shafts	Torsional	700
Gear box	Fatigue life tests in service	80
Crankshafts	Fatigue life tests in service	3000 but highly variable
Aircraft coupling rods	Tensile-compression	105
Driving rods	Tensile-compression	45
Cam springs	Dynamic stress	100 to 340
Helical springs	Fatigue life in service	3500
Torque rods	Dynamic stress	140 to 600
Universal joint shaft	Reverse bending	350
Gear wheel	Fatigue life tests	130
Tank chain	Fatigue life tests	1100
Weld	Fatigue life tests	200

Valve	Fatigue life tests	700
Rocker arm	Fatigue life tests	320

Tableau 3. Increase in the fatigue life of various mechanical components as a result of shot-peening



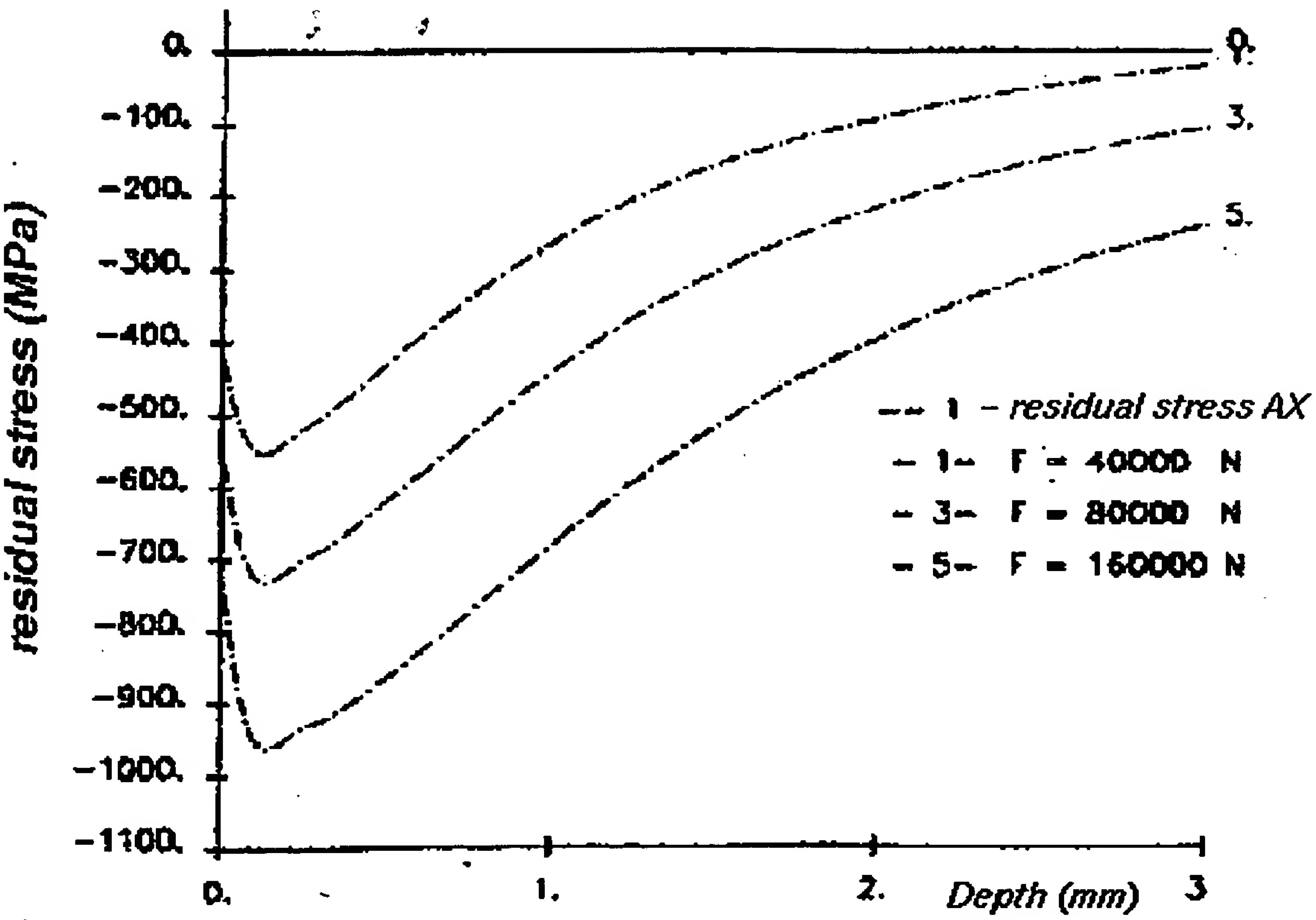
1. Effectiveness of roller-burnishing in increasing the fatigue strength



2. *Beneficial effect of various surface treatments on the fatigue strength (maximum gain reported in the literature)*

The second phase consists in predicting the fatigue life using the notions developed in chapter 5.

3. *Final incorporation of residual stress into the design office*



4. *Modelling the residual stress produced by roller burnishing of a titanium alloy (TA6V,) influence of the applied load during burnishing*

EFFECT OF INCORPORATING RESIDUAL STRESS ON QUALITY ASSURANCE

We have seen how residual stress can be incorporated into the design of mechanical components. But although this leads to a better knowledge of the fatigue life of parts and reduces the safety coefficient at the design stage, it also poses a host of new problems on a quality assurance level. All statistical controls are only applied today to a few critical components in the aeronautical and nuclear industries, this practice could easily become widespread. Rapid ways of checking the residual stress must therefore developed. The methods used industrially (X-ray diffraction and the incremental hole method) will not be sufficient in the future. NDT techniques (ultrasound, magnetic methods, acoustic emission) are presently being developed. But as they currently stand, these techniques use physical parameters which depend not only on the residual stress present in the parts but also on micro-structural changes. In the near future, NDT techniques will be applied at the same time as the reference techniques. Figure 20 proposes residual stress inspection plan.

1. *Residual stress inspection plan for the purposes of quality assurance..*

FINAL CONCLUSION

Residual stress plays a very important role with respect to the different properties of materials. The gain obtained from the presence of residual stress can be enormous. This article attempts to show the effects of residual stress through the example of fatigue strength. Here, we have shown that it is now possible to predict the fatigue strength of materials taking residual stress into account. Although, we are not in a position to provide the same type of calculation tools for other properties such as corrosion resistance and the adhesion of coatings, it is now reasonable to expect that the notion of residual stress will be gradually introduced into the design stage of mechanical parts. Numerical modelling of the

behaviour beforehand saves a considerable amount of time because of the reduction in the number of experimental tests required. These tests are often very long and costly, but they have proved to be indispensable. The problem of taking residual stress into account at the design stage will become more and more critical with the development of new materials (multi-materials, etc.) and new treatments (combined treatments, etc.)